Past and Future of Exoplanet Characterization and Statistics

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DLR Deutsches Zentrum für Luft- und Raumfahrt e.V.
in der Helmholtz-Gemeinschaft

An excuse

This summer school intends presenting ...the modern instruments available for observations in the Optical and IR domain, together with their science cases and performances.

...hands-on experience on data reduction (archive data)...

The work will be accompanied by lectures on "Hot topics in Astrophysics", a tutorial on VO astrophysics, as well as a tutorial on "How to write a (good) telescope time request proposal".

My goal to contribute to the part...

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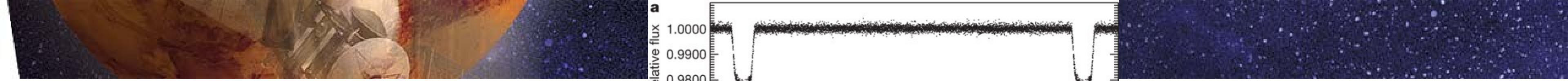
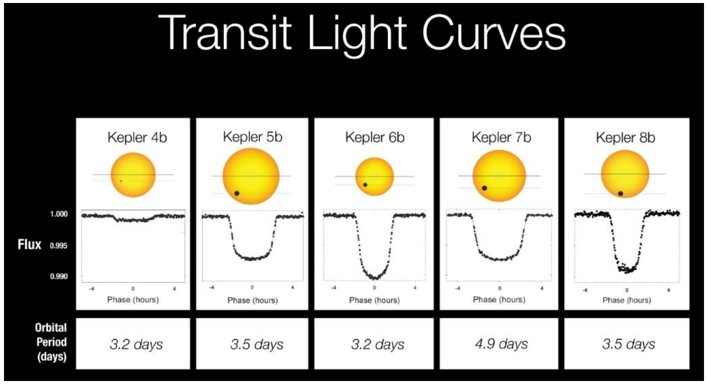
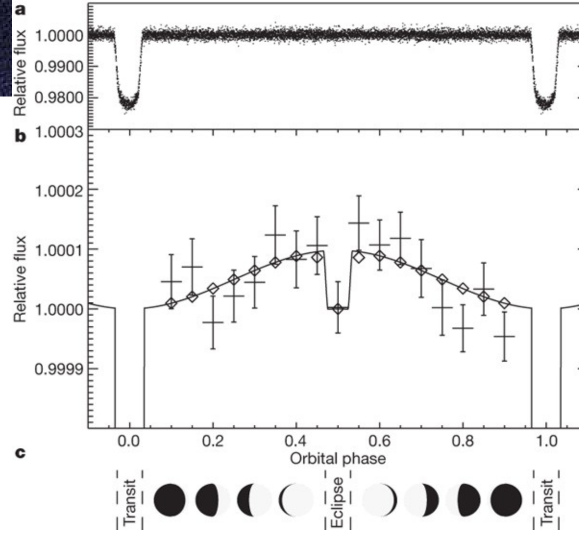
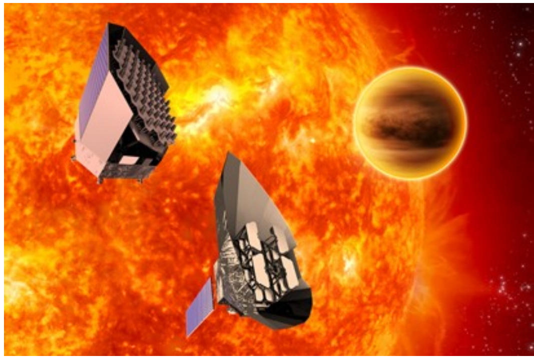




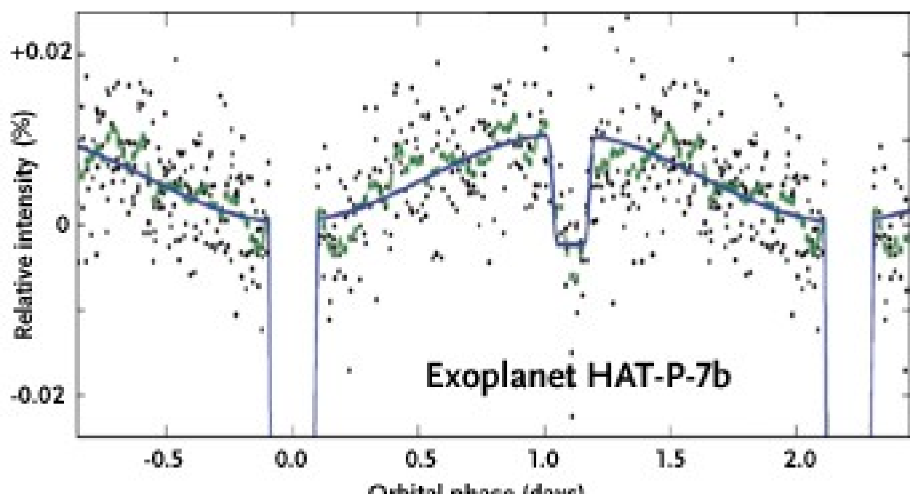


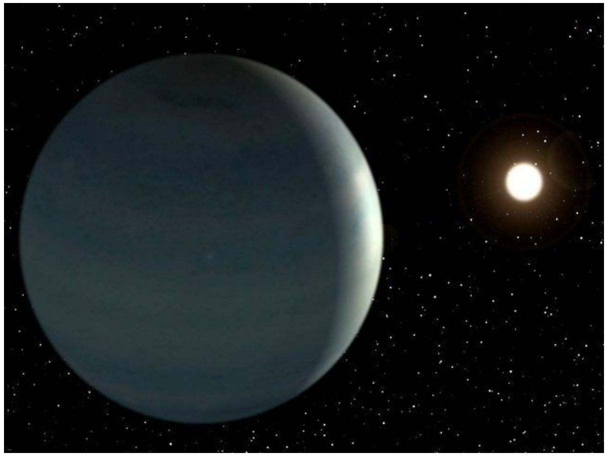


/NASA/Kepler/

CoRoT-1b (Snellen et al. 2010)

Past and Future of Exoplanet Characterization and Statistics





/Borucki et al. 2009/, Science

CoRoT-9b, Deeg et al. (2010), Nature

Outline

1. Motivation
2. Milestones
3. What is a planet?
4. Main observational techniques
5. Curiosities and statistics
6. Occultations, phase curves, atmospheres, composition, ...
7. Future

1. Motivations of exoplanet researches

1. Frequency of planetary systems in the Universe.
2. Formation, dynamics and evolution of planetary systems.
3. Composition and internal structure of planets.
4. Life in the Universe.

2. Milestones
History of Exoplanet Researches

1./ A very few scientists and philosophers in the ancient times and middle-ages : planets may be / should be existing orbiting other stars than Sun.

2./ Struve (1952) proposes the transit-method.

3./ 1989: an exoplanet suspected first time by RV-method (many years later confirmed).

4./ 1992: first exoplanetary system around a pulsar

5./ 1995: discovery of 51 Pegasi b (Mayor & Queloz) by RV-method.

6./ 2000: first transit observations.

7./ 2002: first planet discovered by the transit method.

8./ 2008: first brown dwarf in the so-called ´BD-desert'

9./ 2009: first Earth-like planets announced

10./ Ca. 2007-2010: first transit spectroscopy, atmosphere studies

11. Ca. 2010-2014: first planets in Habitable Zone (`Liquid Surface Water Zone´, Shapley 1938)

12./ 2014: first Solar Analogue-discovery

3. What is an (exo)planet?

"A planet is a celestial body that:

(a) is in orbit around the Sun

(b) has sufficient mass for its self-gravity to overcome rigid body forces so that it assumes a hydrostatic equilibrium (nearly round) shape, and

(c) has cleared the neighbourhood around its orbit." IAU, Resolution B5

- Why Pluto? "It is not a planet..."
- What about floating planets?
- What about planets around neutron stars?
- Why different definition for planets and exoplanets??

"Extrasolar planet is:
an object that has a mass between that of Pluto and the deuteriumburning threshold and that forms in orbit around an object that can generate energy by nuclear reactions“
G. Marcy

Astrophysical definition

Stars: over 80 Jupiter-masses (hydrogen-fusion and later stages if mass is large enough)

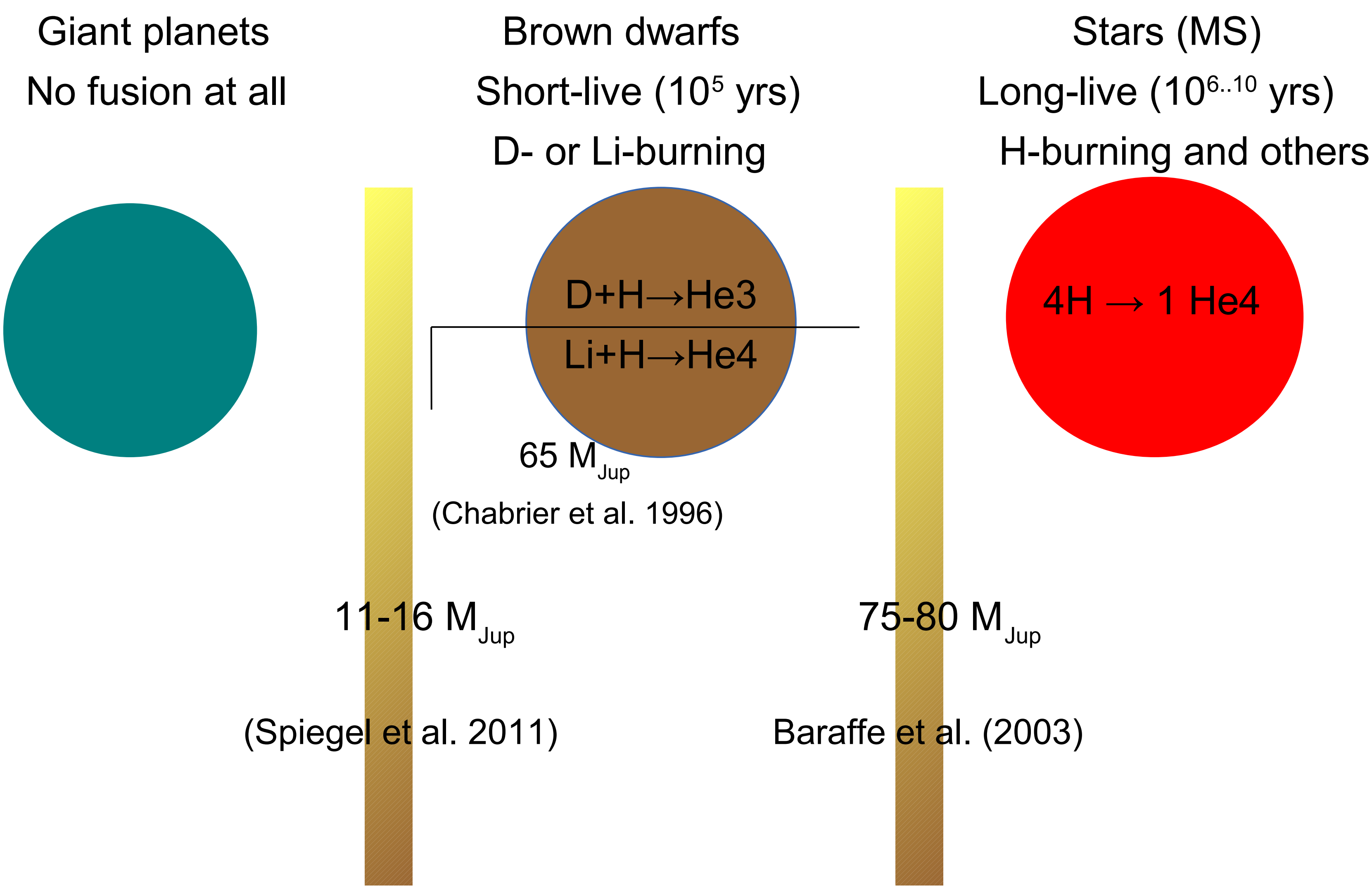
Brown dwarfs: between 13-80 Jupiter-masses (only deuterium-fusion)

Planetary bodies: below 13 Jupiter-masses (no natural fusion)

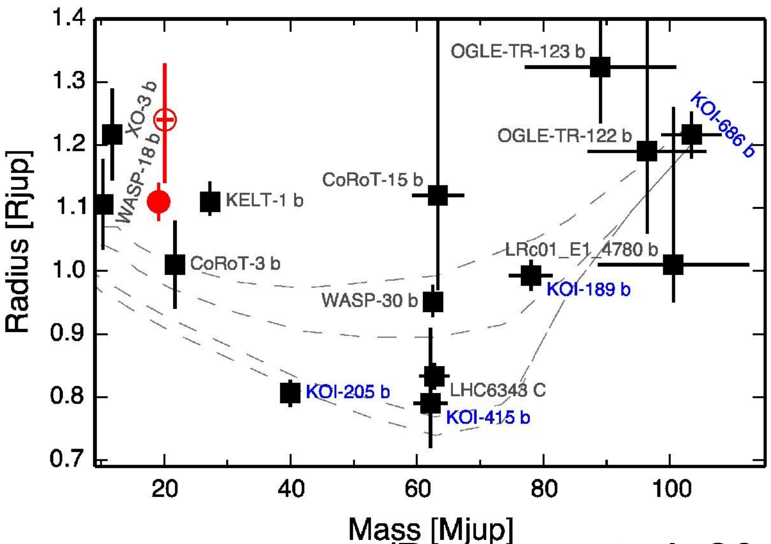
These mass limits depend slightly on the chemical composition.

But: (i) no definition from giant planets, dwarf planets, asteroids, meteors etc. in this astrophysical definition; (ii) upper limits can depend on chemical composition.

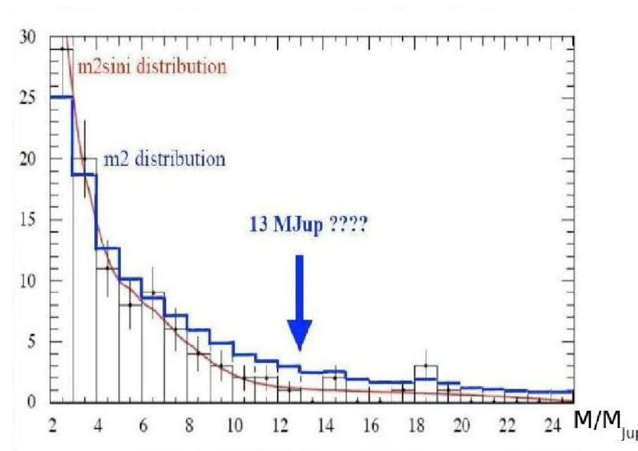
What are brown dwarfs?



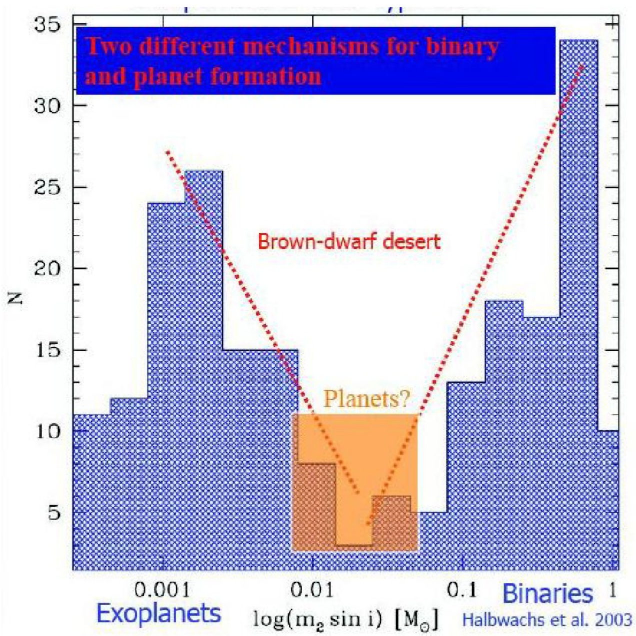
How to separate brown dwarfs from giant planets?



/Bonomo et al. 2015/

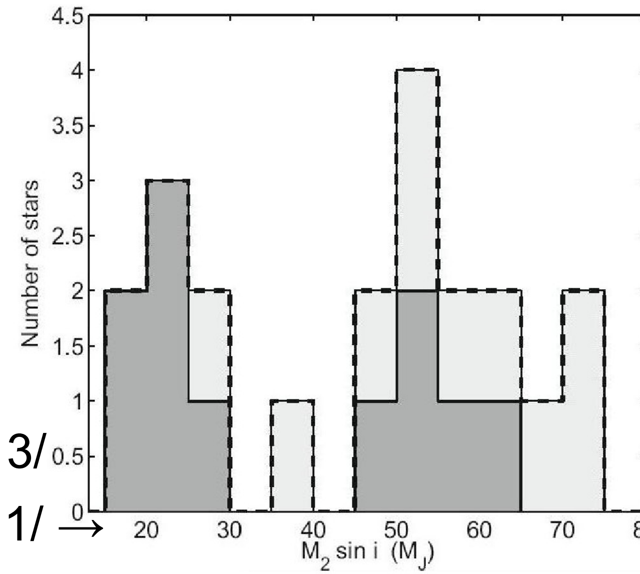


/Udry et al. 2010/



← /Halbwachs et al. 2013/

/Sahlmann et al. 2011/ →



How many brown dwarfs are known in total,

in binary systems,

as transiting one?

W. R. Johnston (2015 June 14):

http://www.johnstonsarchive.net/astro/browndwarflist.html

1960 confirmed planets, but

2179 brown dwarfs are known.

427+ are in binary systems.

Ma & Ge (2014, MNRAS 439, 2781):

65 brown dwarfs are closer than 2 AU to FGK dwarfs.

9 or 10 brown dwarfs are <u>transiting</u>, including this new one.

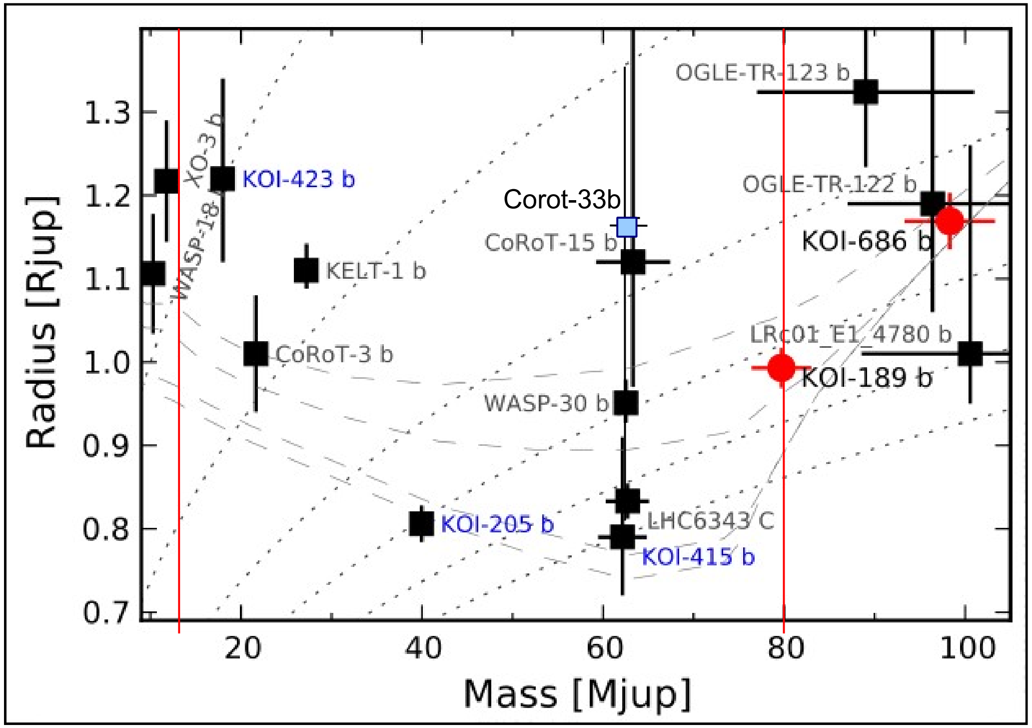


Figure: M. Deleuil. *Data sources: Deleuil et al., 2008; Bouchy et al., 2011a, 2011b, Johnson et al., 2011, Siverd et al. 2012, Moutou et al., 2013, Diaz et al., 2013, 2014; Anderson et al. 2011, Csizmadia et al., (submitted)*

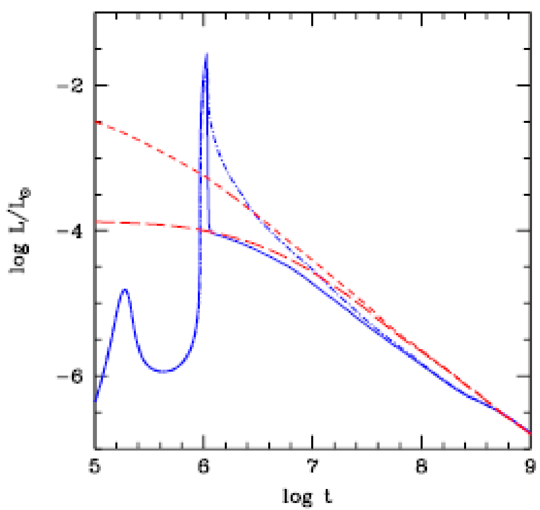
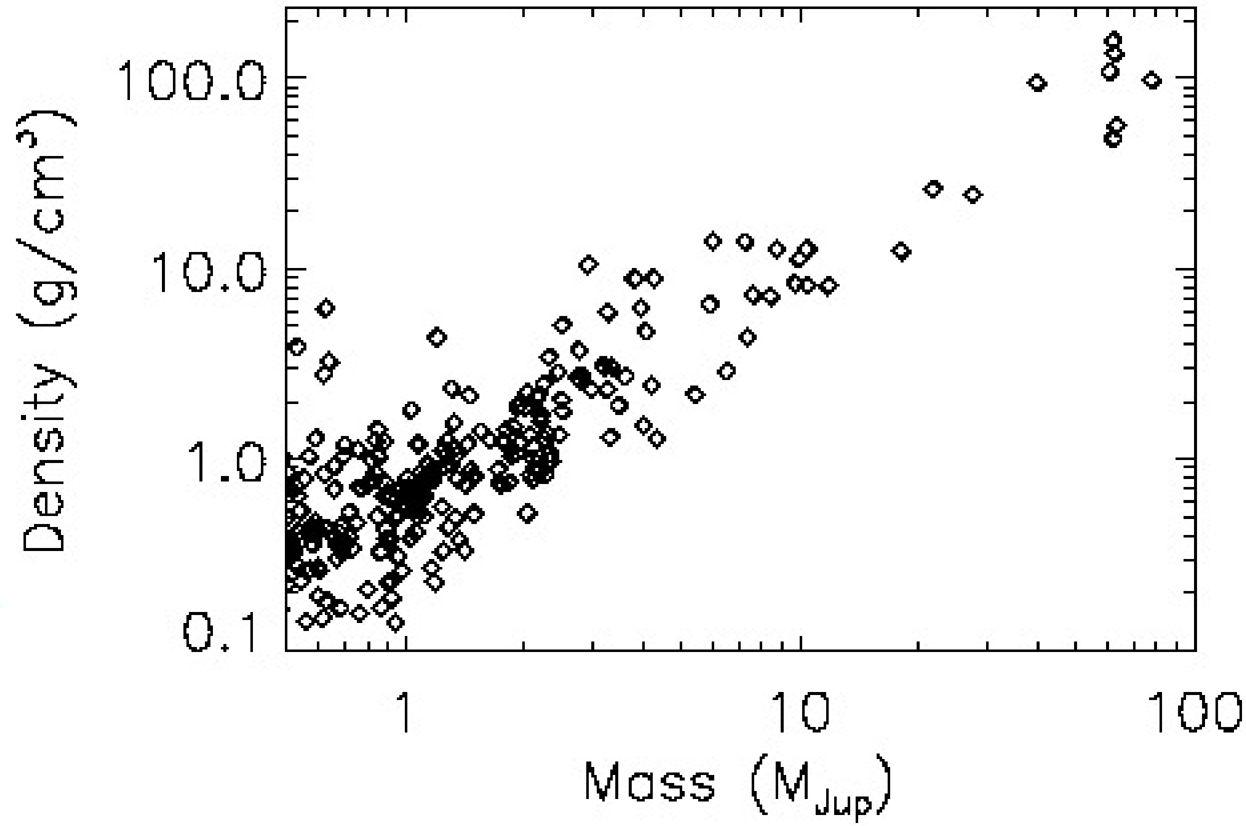
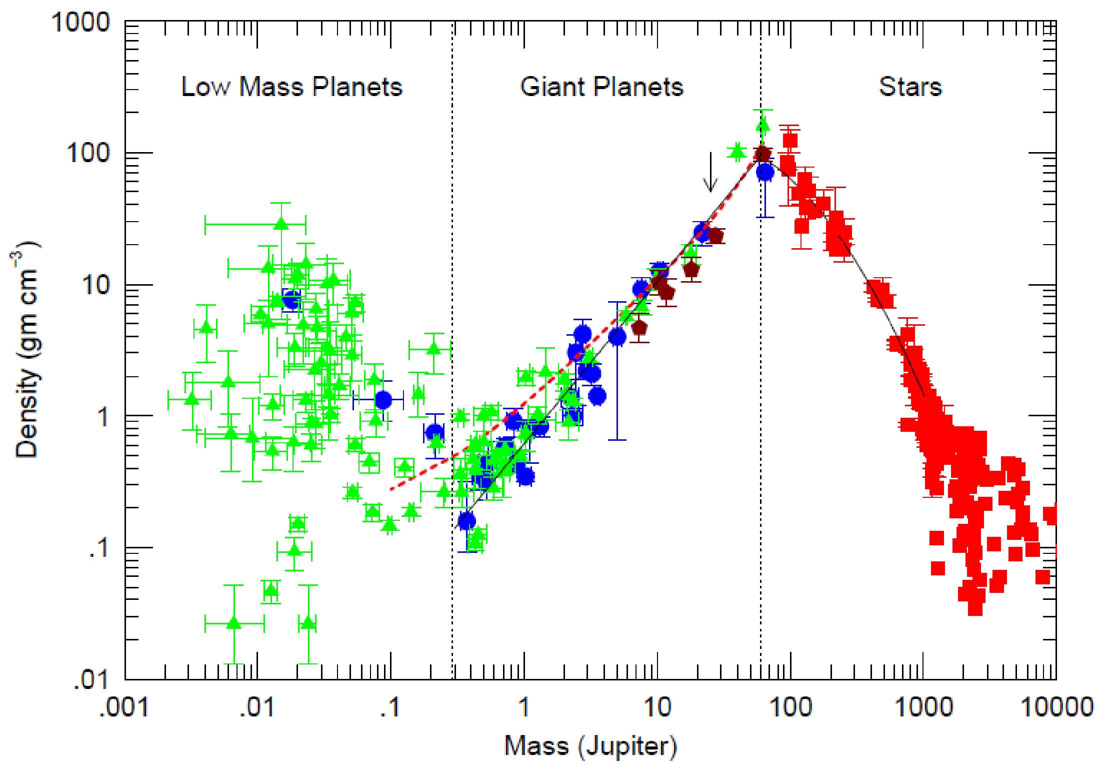


Fig. 2.— Early evolution of a 5 Jupiter-mass object according to different formation scenarios. Blue: object formed by core accretion assuming either a supercritical shock (solid line) or a subcritical shock (dash-dot line) at the end of the accretion process, after *Mordasini et al.* (2012a). Red: object formed by gravitational collapse for two arbitrary initial conditions (see text), after *Baraffe et al.* (2003)

/Chabrier et al. 2014/

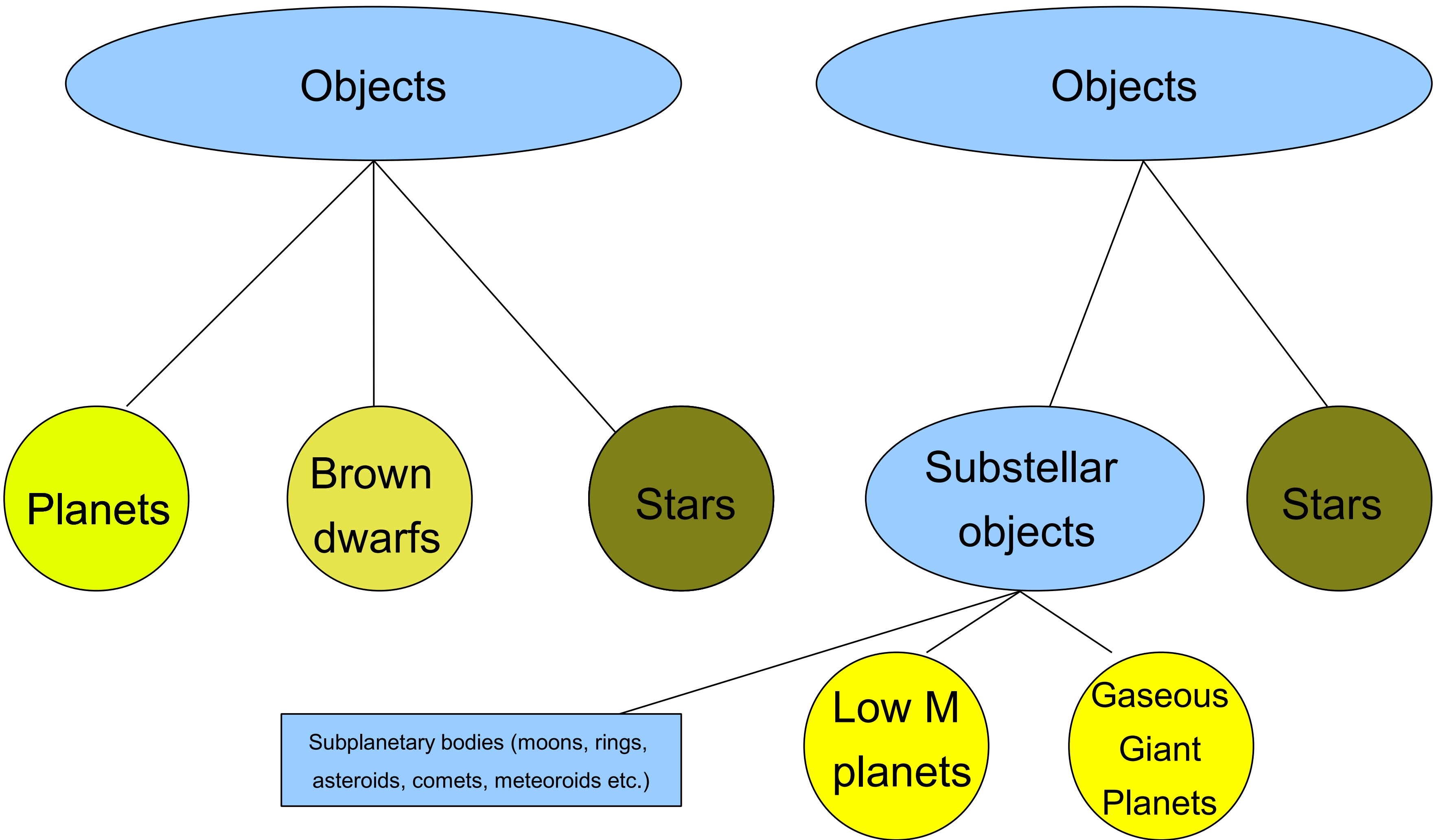




Hatzes & Rauer 2015, ApJ, in press

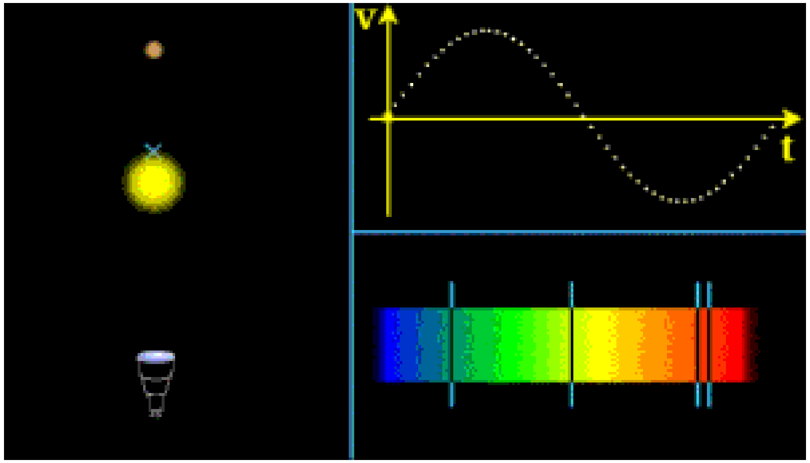
Fig. 1.— The density and mass of stars (red squares), giant planets and brown dwarfs, and low mass planets. Triangles represent Kepler discoveries and dots are CoRoT exoplanets. Ground-based discoveries for high mass giant planets are shown by pentagons. The line represents a linear fit to the giant planets and brown dwarfs in the mass range $M = 0.35$ - $60\ M_{Jup}$. A second order polynomial fit (curved line) was made to the lower end of the stellar main sequence. The boundary between the low mass planets and giant planet occurs at $M = 0.3\ M_{Jup}$. The boundary between the giant planets and stars is at $M = 60\ M_{Jup}$ ($0.060\ M_{\odot}$). The dashed red line shows the mass-density relationship for H/He dominated giant planets taken from Fortney et al. (2007).

A clear classification scheme needs observables (formation is not that one), like mass, radius, luminosity, mean density, orbit, composition, ...

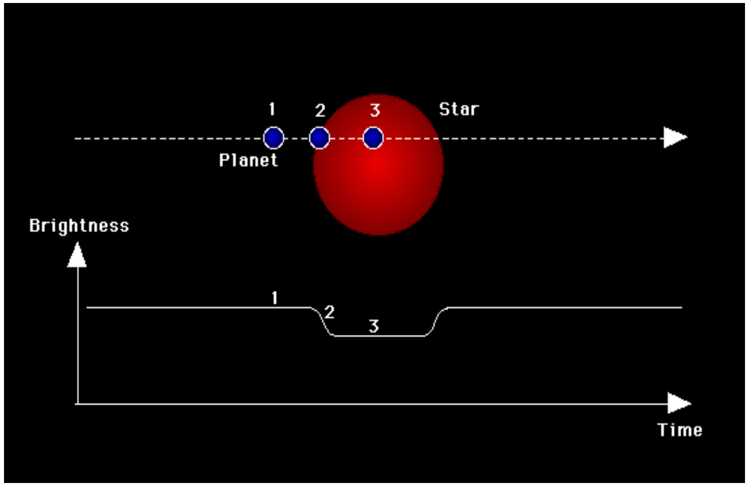


4. Main observational techniques and challanges

Radial Velocity Method



Transit Method



→ Orbital parameters

→ lower limit on mass

(m *sin* i)

→ Orbital parameters

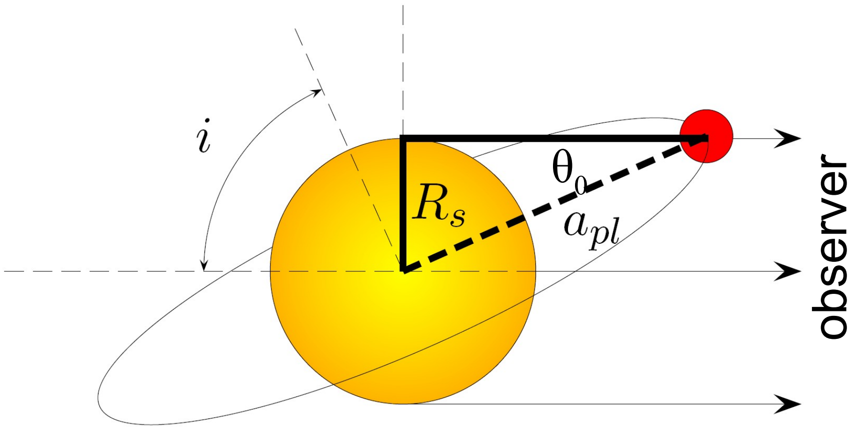
→ inclination i

→ planet radius

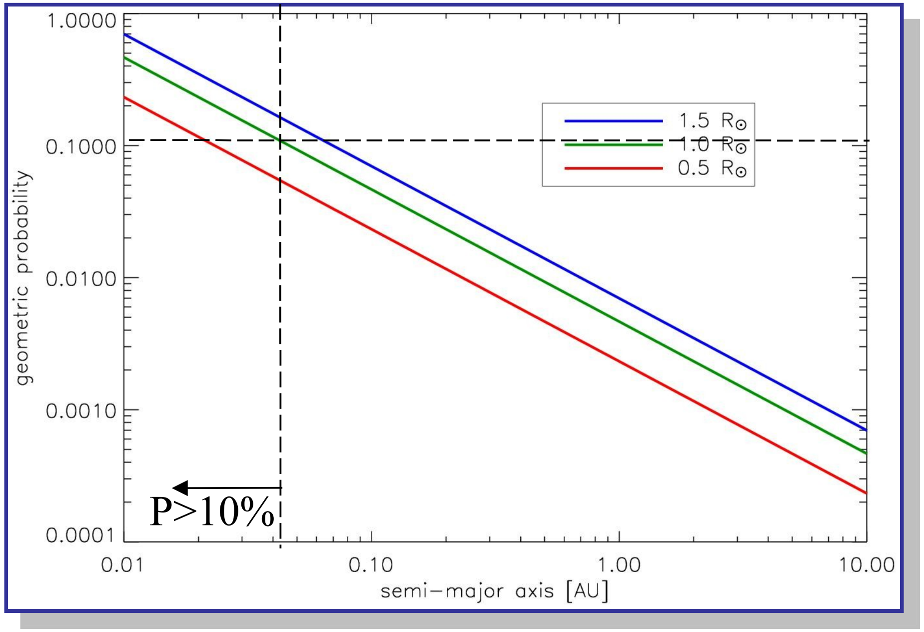
True mass and mean density

The probability of transits

Geometrical probability:



The observer must see the planetary orbit edge-on to observe a transit!

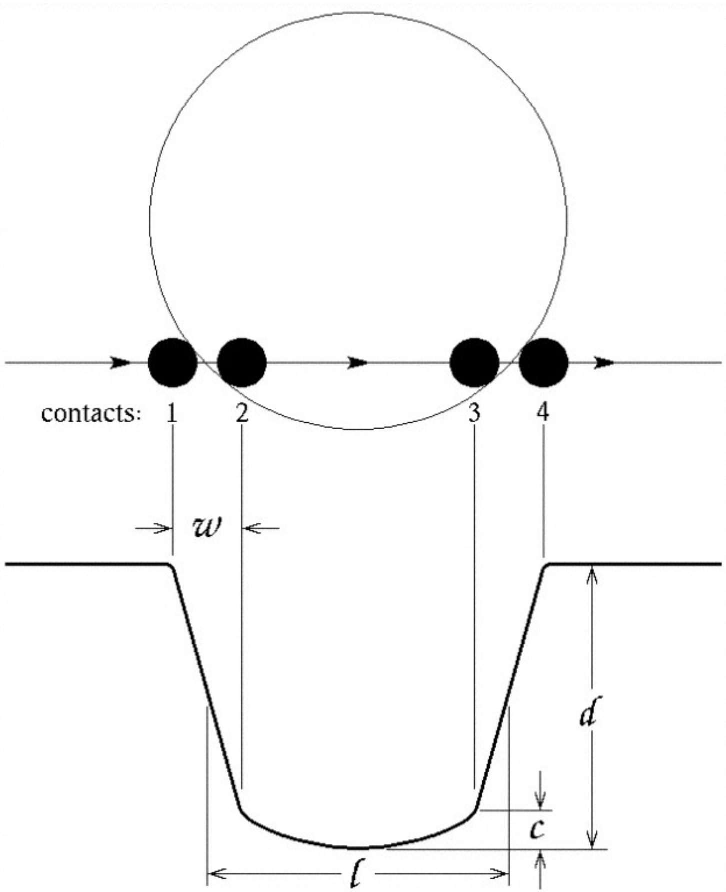


Geometric transit probability:

$$P = \frac{\int_0^{\theta_0} \cos\theta d\theta}{\int_0^{\pi/2} \cos\theta d\theta} = \frac{\sin\theta\big|_0^{\theta_0}}{\sin\theta\big|_0^{\pi/2}} = \frac{\sin\theta_0}{1} = \frac{R_s}{a}$$

For excentric orbits:

$$P_t = \frac{(R_p + R_\star)\left(1 + e\cos\left(\frac{\pi}{2} - \omega\right)\right)}{a\left(1 - e^2\right)}$$



Duration l depends on the orbital speed (which can be estimated from the period and the stellar mass), and on the orbital inclination i and on the sum of the radii $R_p + R_s$.

Depth d depends mostly on the area ratio R_p^2/R_s^2, and slightly on the inclination and the limb darkening.

Ingress/egress time w depends on the orbital speed, on the planetary radius R_p, and on the inclination.

Bottom curvature c depends mostly on the limb darkening, and slightly on the inclination.

To derive planet parameters we need to combine photometric transits with stellar parameters

Planet radius:

R_S from:

k: fitting parameter from transit lightcurve:

$$k = \frac{R_{pl}}{R_S}$$

- ph

-

- dir

Planet mass:

from radial-velocity

from transit lightcurve or rv

i fr

$$\frac{K^3 P}{2\pi G} = \frac{M_{pl}^3 \sin^3 i}{\left(M_{pl} + M_S\right)^2}$$

→ the error of planet parameters is usually determined by the errors in stellar parameters

Challanges

- low signal-to-noise ratio

Challanges

- low signal-to-noise ratio
- stellar limb darkening:
  - 1D/3D
  - plane parallel/spherical (Neilson & Lester 2013)
  - granulation (Magic et al. 2015)
  - stellar spots, input stellar parameters, inherent theoretical instabilities (Csizmadia et al. 2013, for spots: Barros et al. 2011, 2014, too)
  - atmospheric convection (Wuchterl, G.; Csizmadia et al. 2013)
  - fitting problems (Csizmadia et al 2013; Espinoza & Jordán 2015)

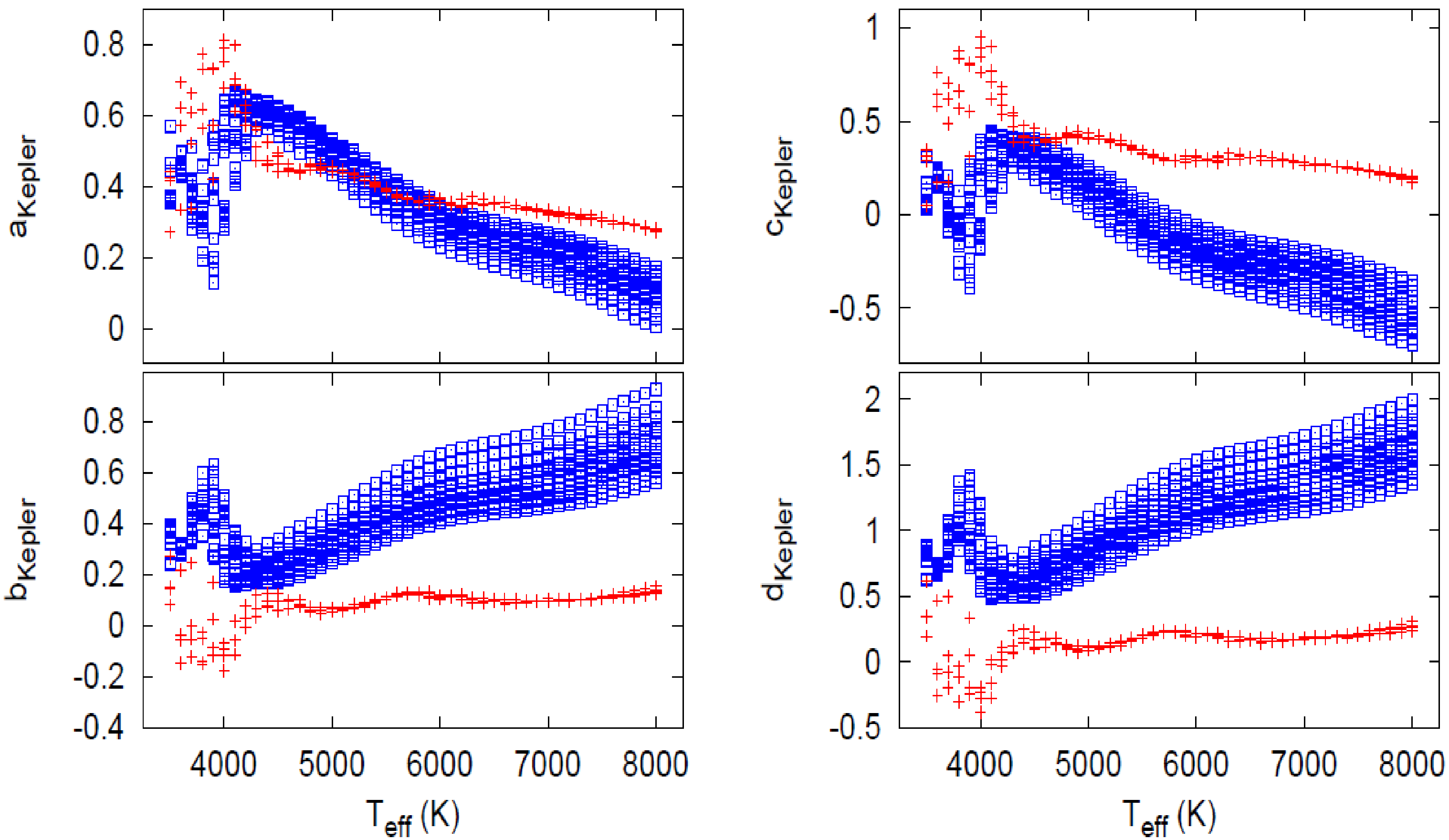


Fig. 3. Limb-darkening coefficients a and b used in the quadratic law (Eq. 2) (left panel), and the coefficients c and d used in the square-root law (Eq. 3) (right panel), all applied to the *Kepler* photometric band. The symbols have the same meanings as in Fig. 2.

Fig. 2. The limb-darkening coefficient u, used in the linear law (Eq. 1), applied to the *Kepler* photometric band. Crosses are the plane-parallel model stellar atmospheres, and the squares are the spherical models.

Challanges

- low signal-to-noise ratio
- stellar limb darkening
- below 1 Msun spots falsify the temperature, luminosity → wrong or suspicious stellar radii (Clausen et al. 2007)

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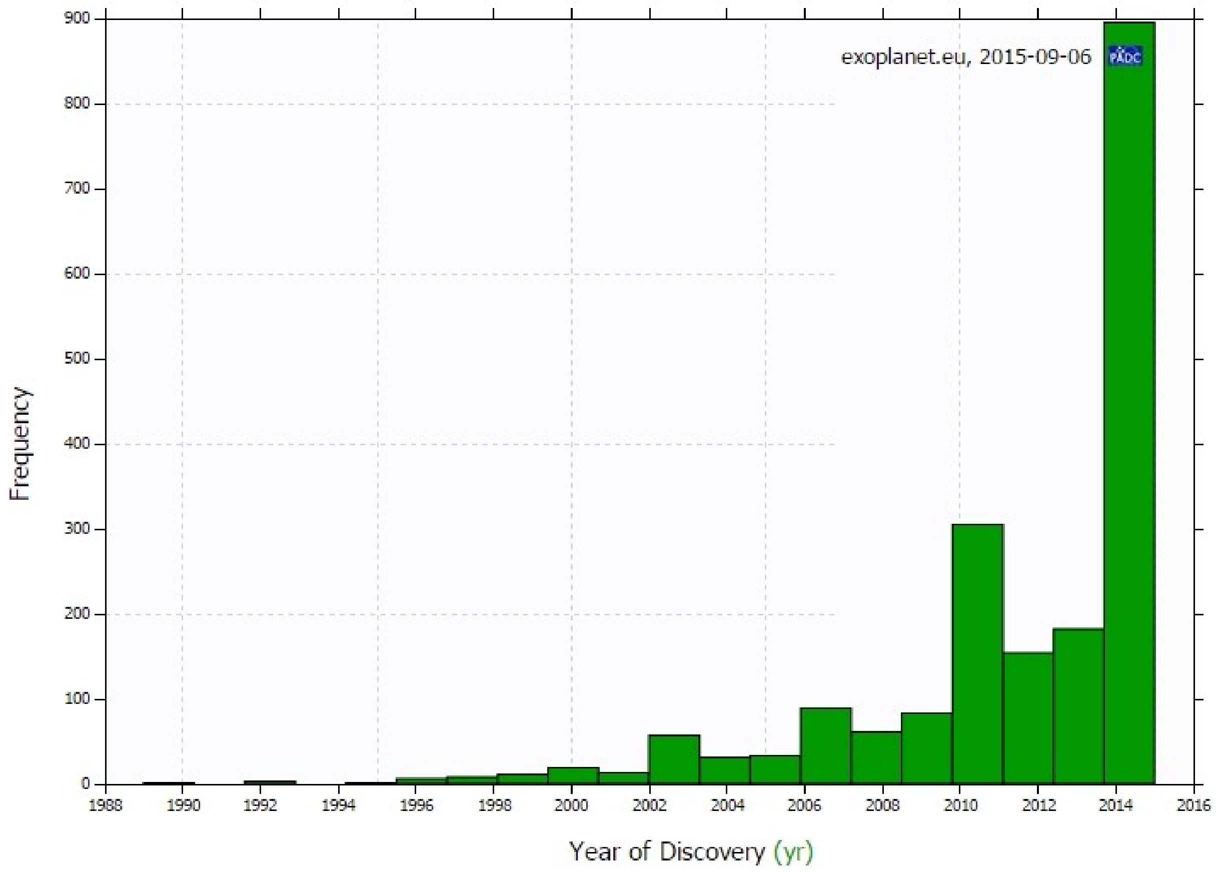
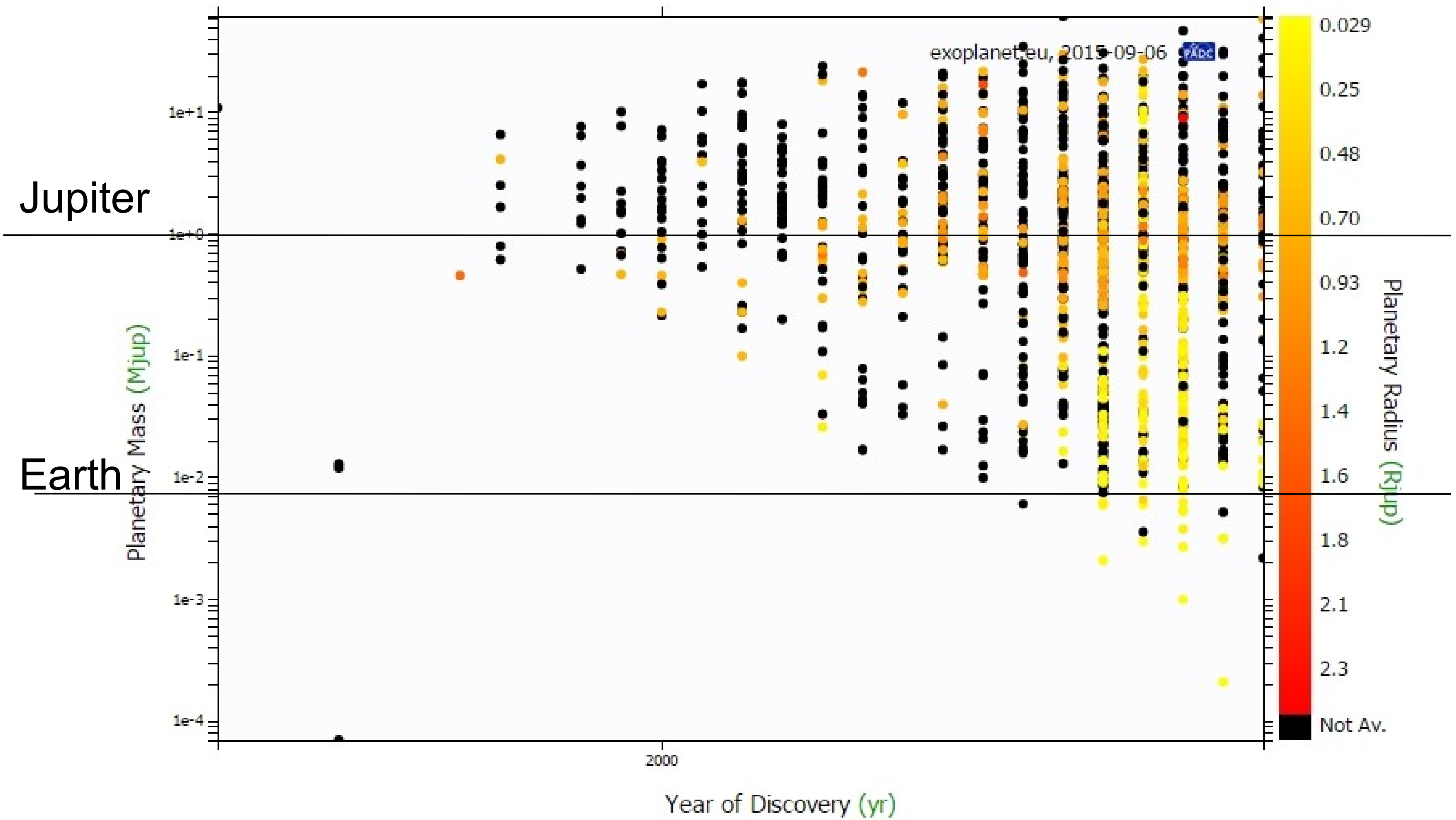
- stellar limb darkening
- below 1 Msun spots falsify the temperature, luminosity → wrong or suspicious stellar radii (Clausen et al. 2007)
- only less than half-dozen dM-stars with well (<3%) measured mass and radii
- calibration problems of isochrones (Gaia?)
- difficulties to measure RV at m/s level (st. jitter – some of the RV-exoplanets just spots...)

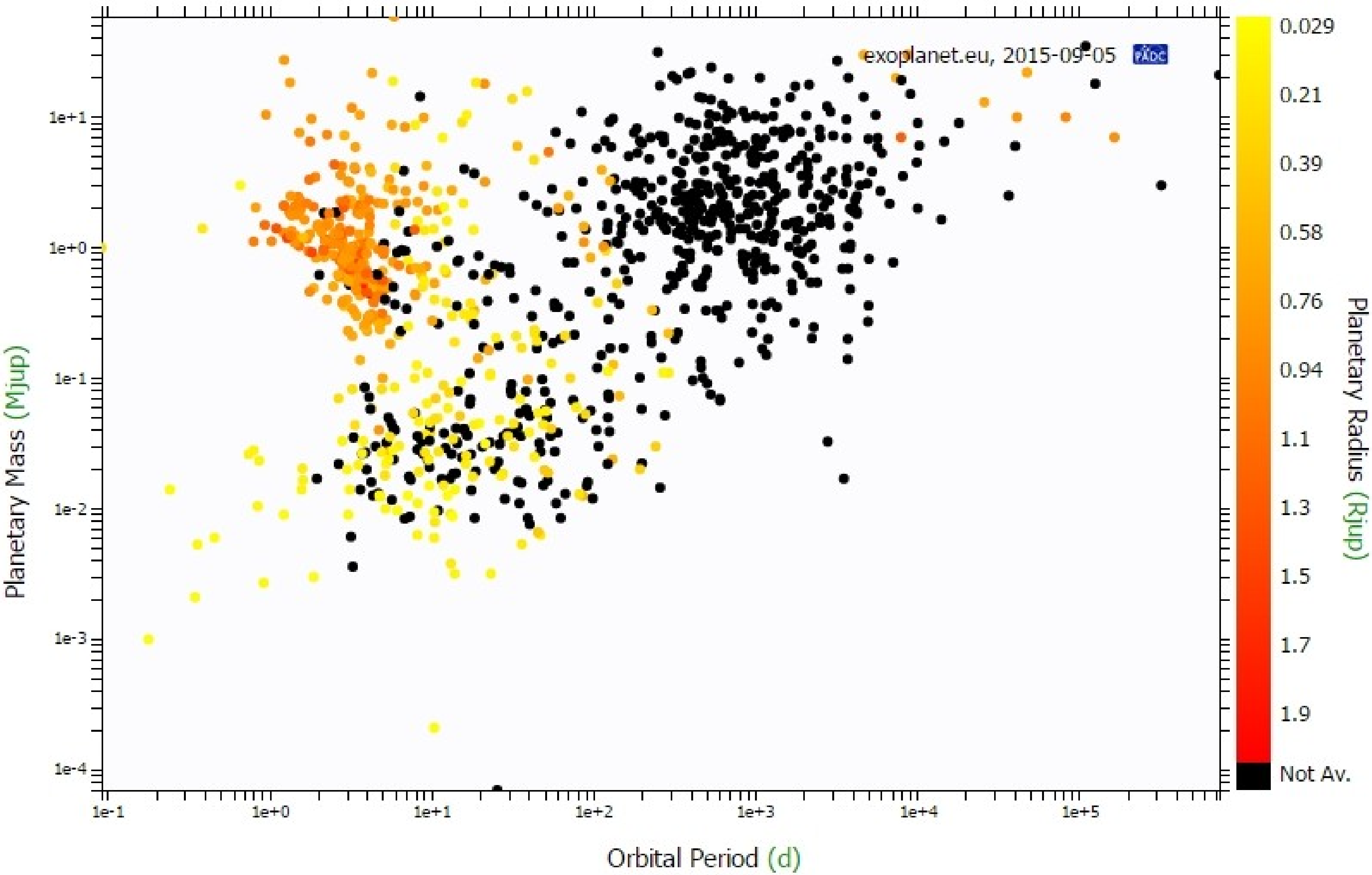
5. Curiosities and statistics



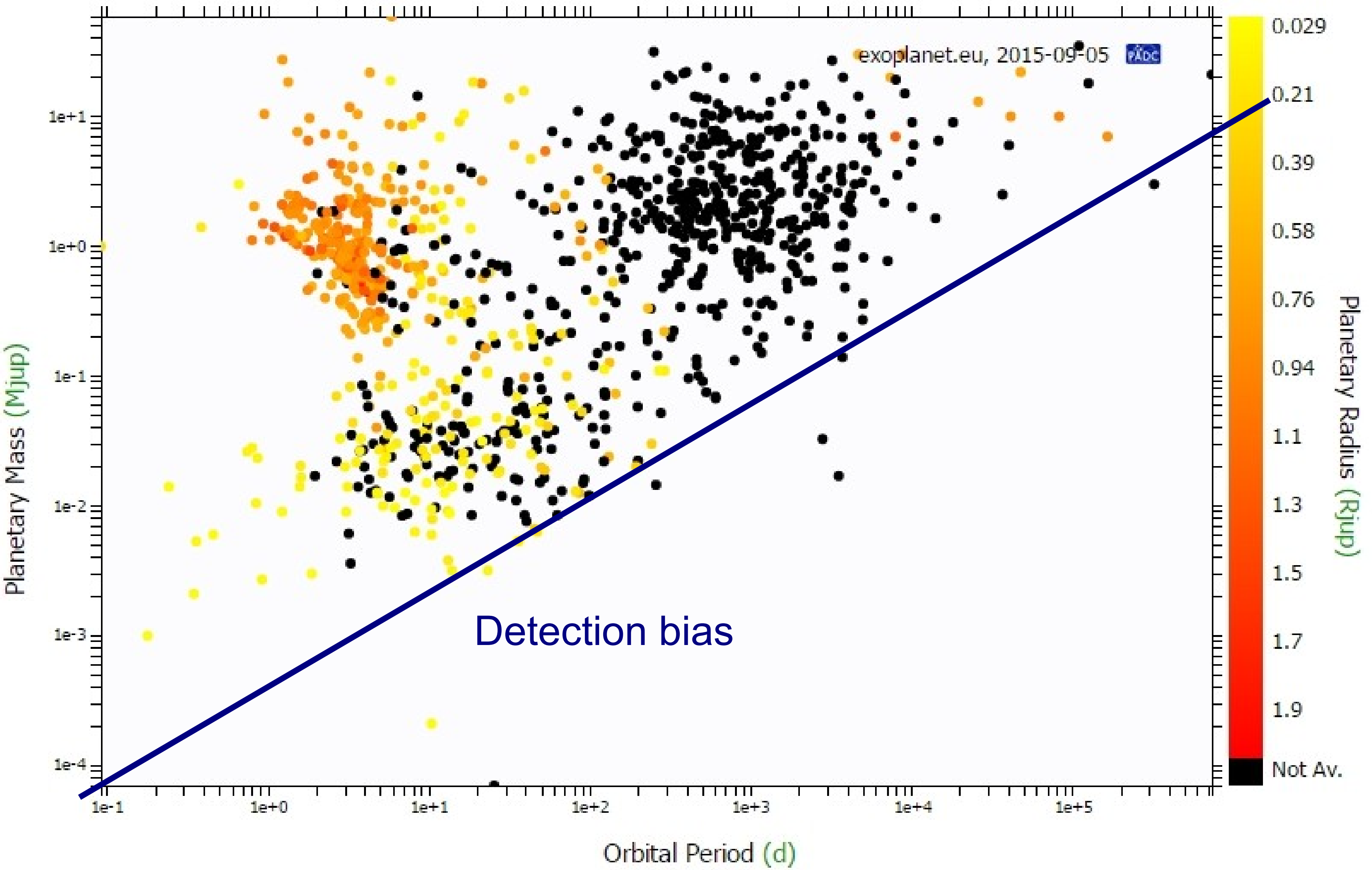
Number of discoveries per year

Toward smaller planets

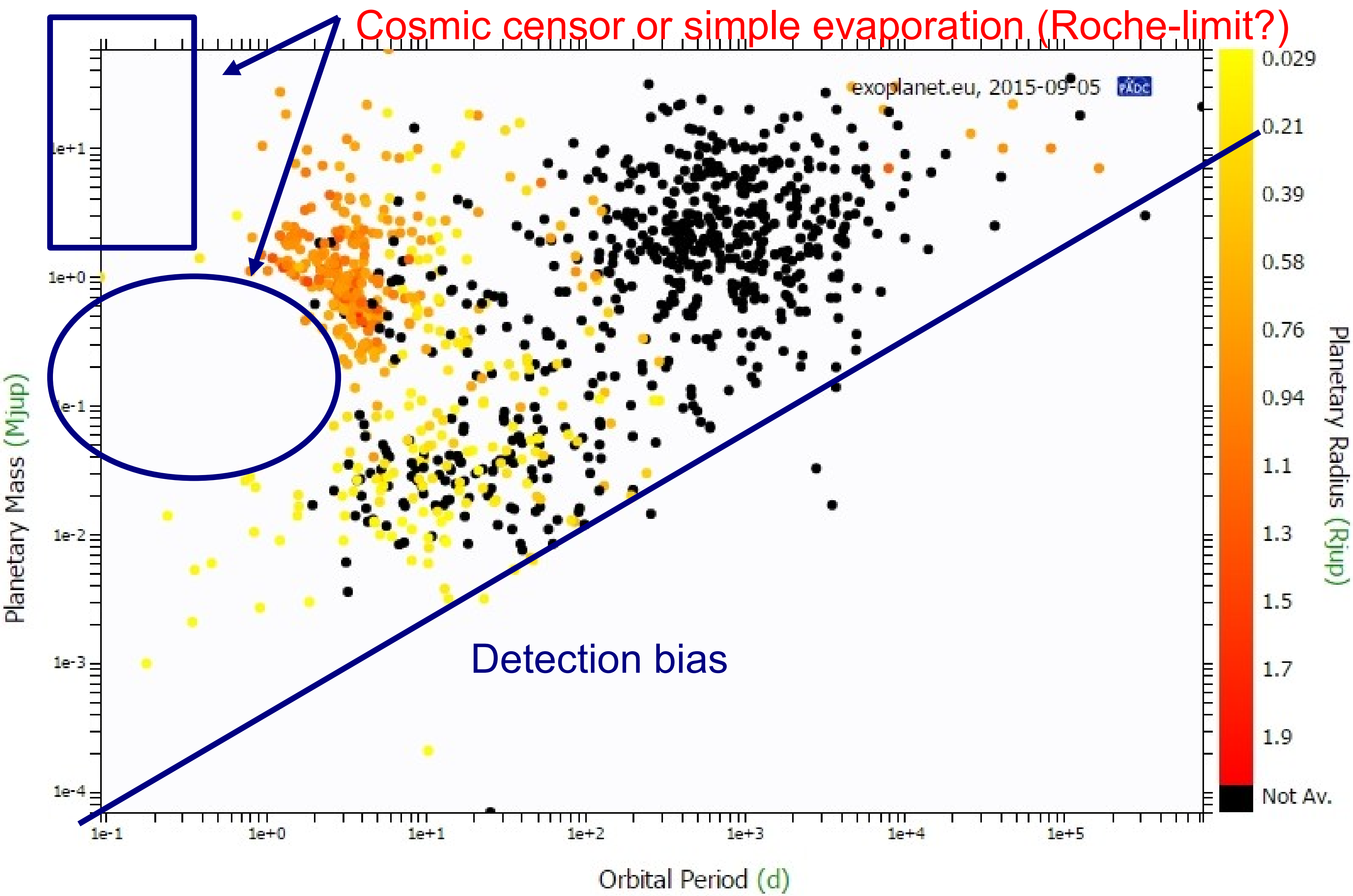




exoplanet.eu, 2015-09-05
Planetary Mass (Mjup)
Orbital Period (d)
Planetary Radius (Rjup)
1e+1
1e+0
1e-1
1e-2
1e-3
1e-4
1e-1
1e+0
1e+1
1e+2
1e+3
1e+4
1e+5
0.029
0.21
0.39
0.58
0.76
0.94
1.1
1.3
1.5
1.7
1.9
Not Av.



exoplanet.eu, 2015-09-05
PADC
Planetary Mass (Mjup)
1e+1
1e+0
1e-1
1e-2
1e-3
1e-4
1e-1
1e+0
1e+1
1e+2
1e+3
1e+4
1e+5
Orbital Period (d)
0.029
0.21
0.39
0.58
0.76
0.94
1.1
1.3
1.5
1.7
1.9
Not Av.
Planetary Radius (Rjup)
Detection bias

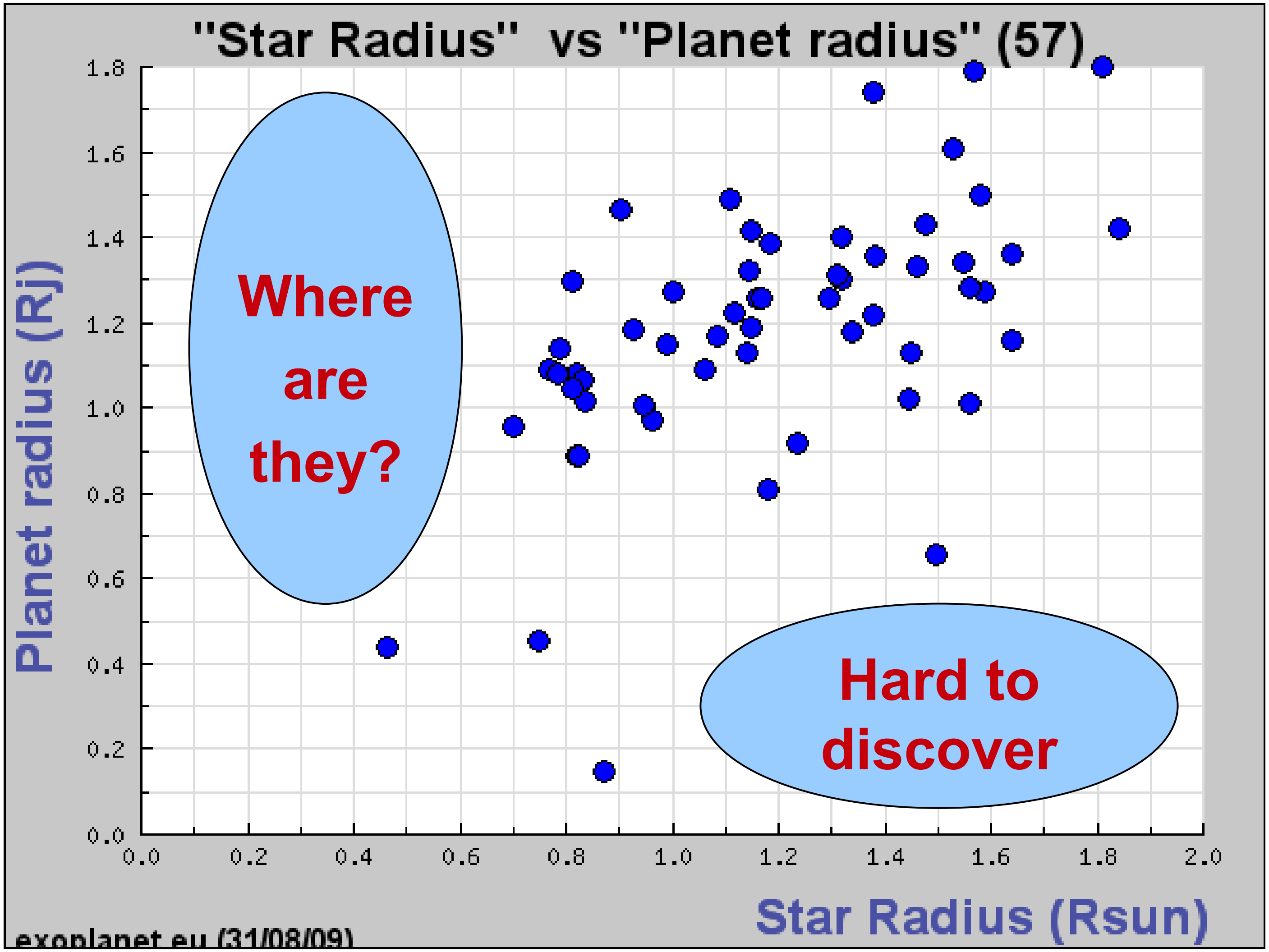


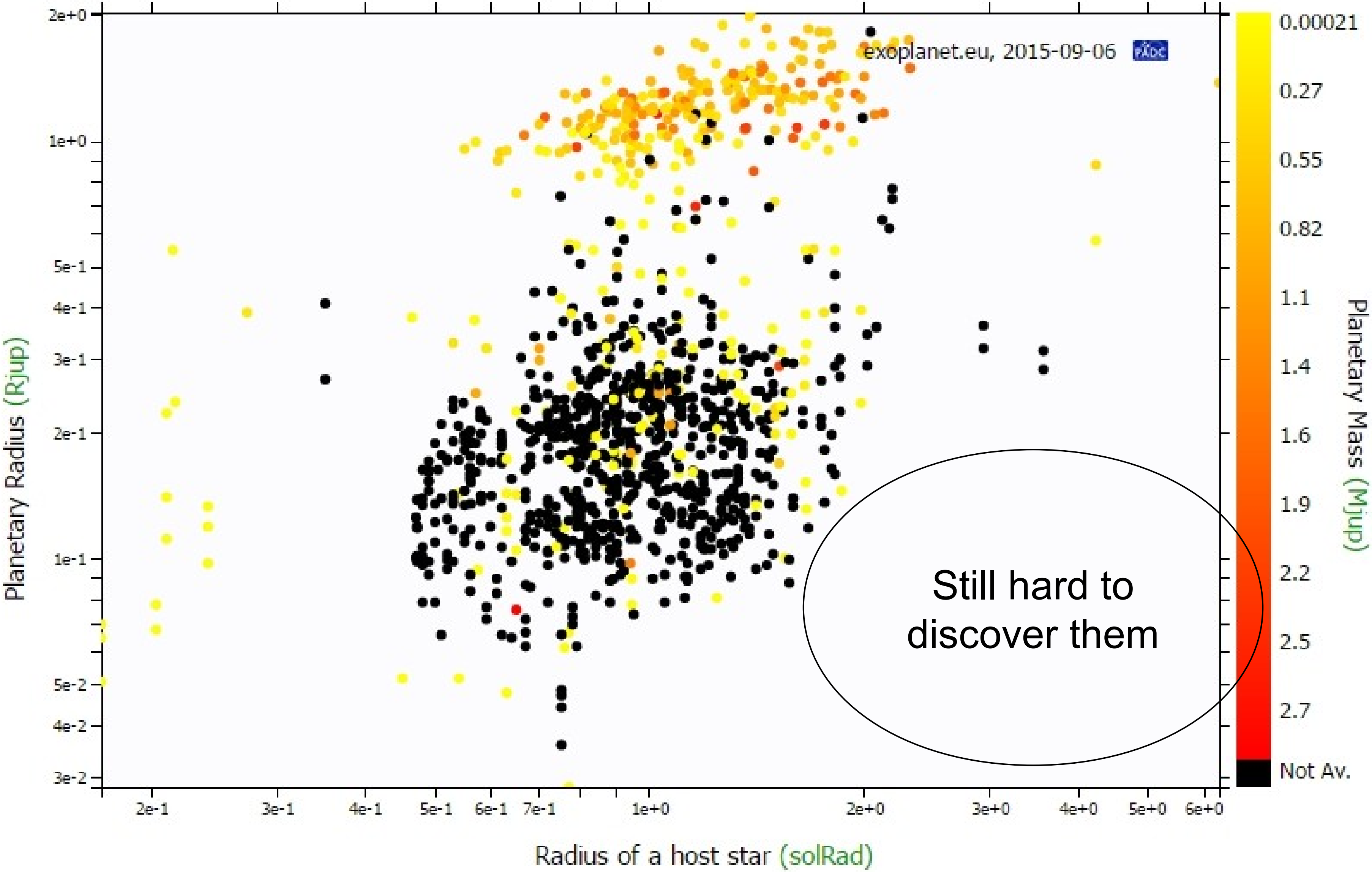
Cosmic censor or simple evaporation (Roche-limit?)
exoplanet.eu, 2015-09-05
Detection bias
Planetary Mass (Mjup)
Orbital Period (d)
Planetary Radius (Rjup)
1e+1
1e+0
1e-1
1e-2
1e-3
1e-4
1e-1
1e+0
1e+1
1e+2
1e+3
1e+4
1e+5
0.029
0.21
0.39
0.58
0.76
0.94
1.1
1.3
1.5
1.7
1.9
Not Av.

Larger planet with larger star??

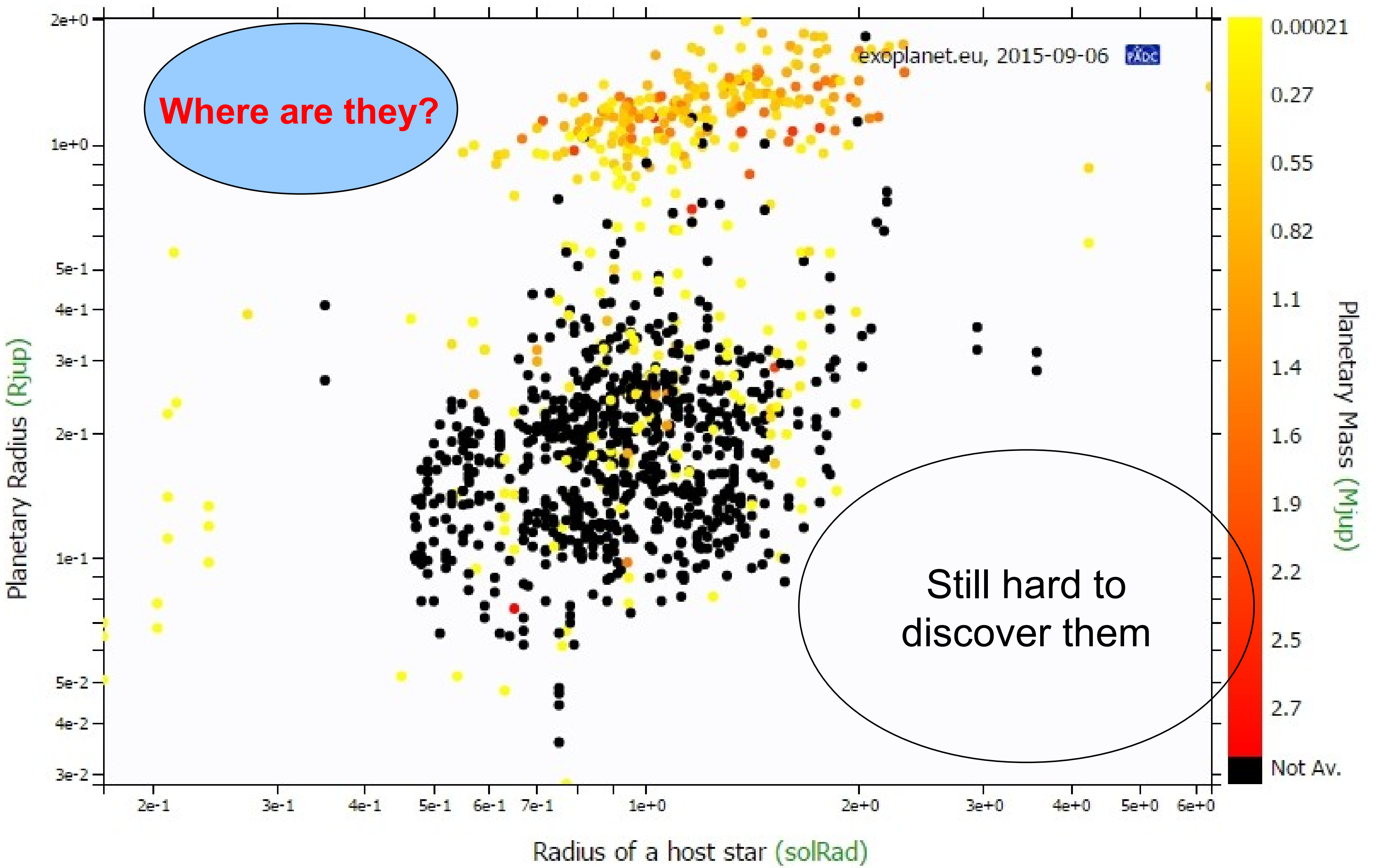
Deuleil et al. (2008):

Larger star with larger planet?





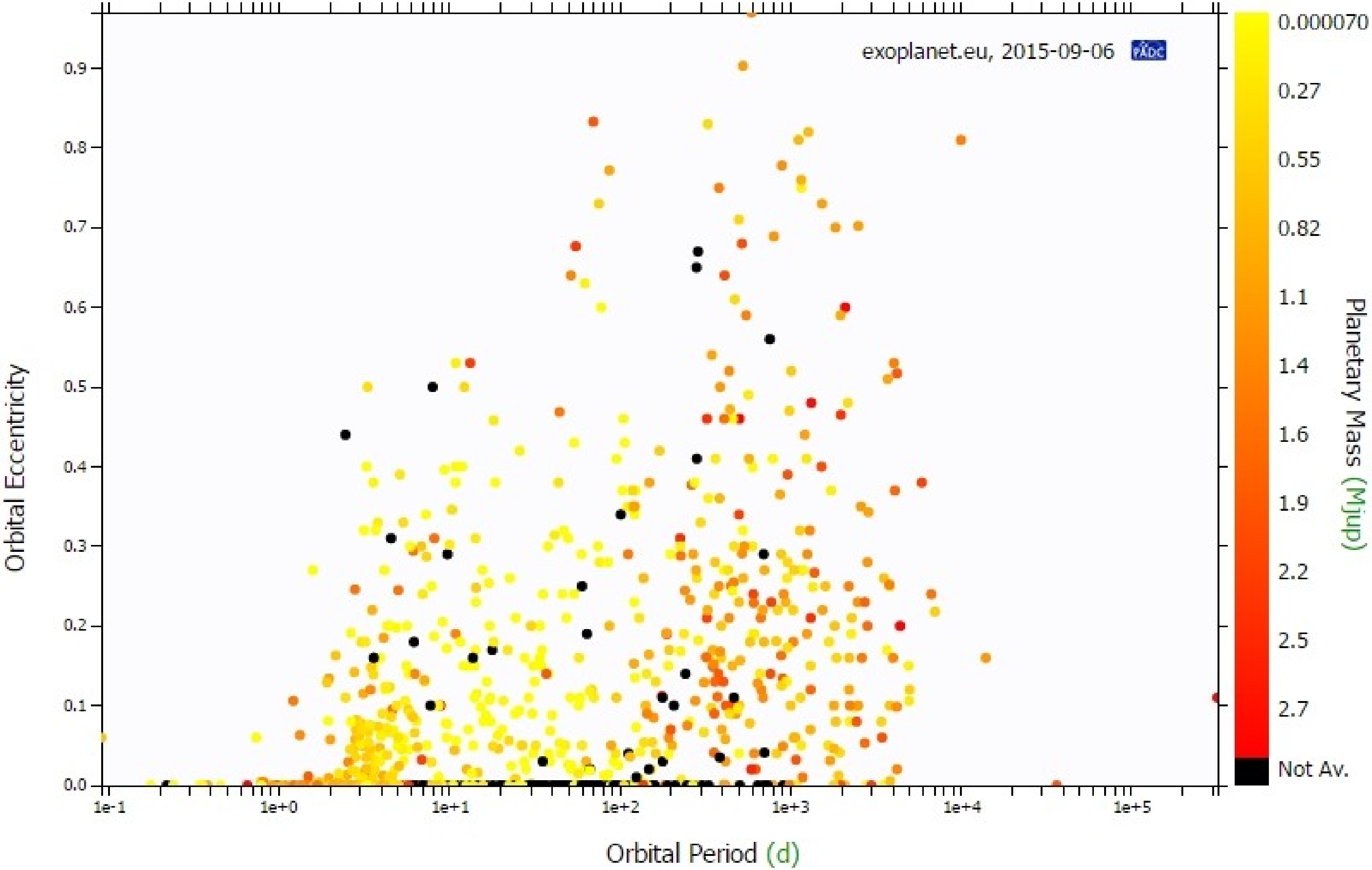
Still hard to discover them



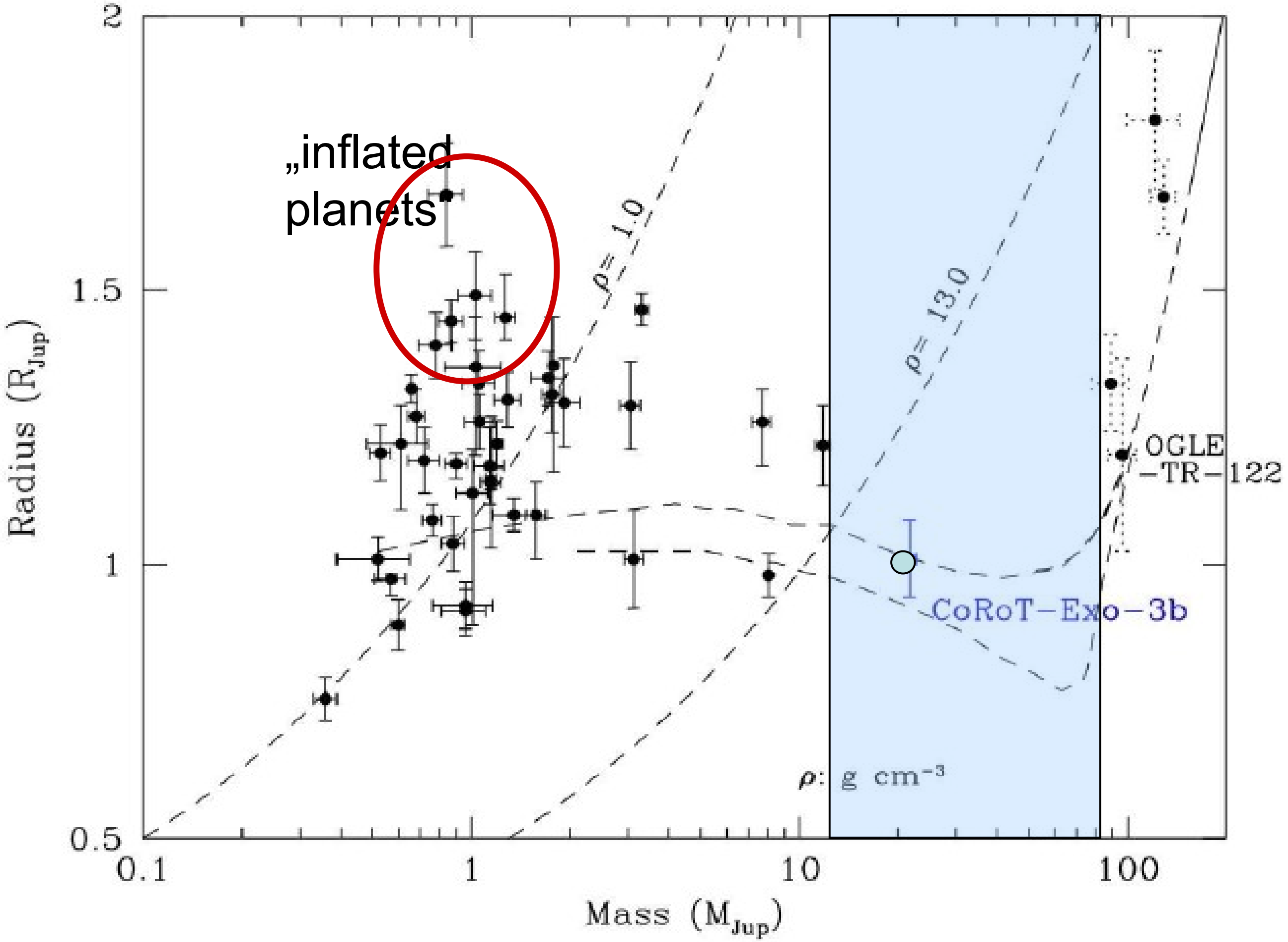
Where are they?

Still hard to discover them

Very large eccentricities



Mass radius relationship

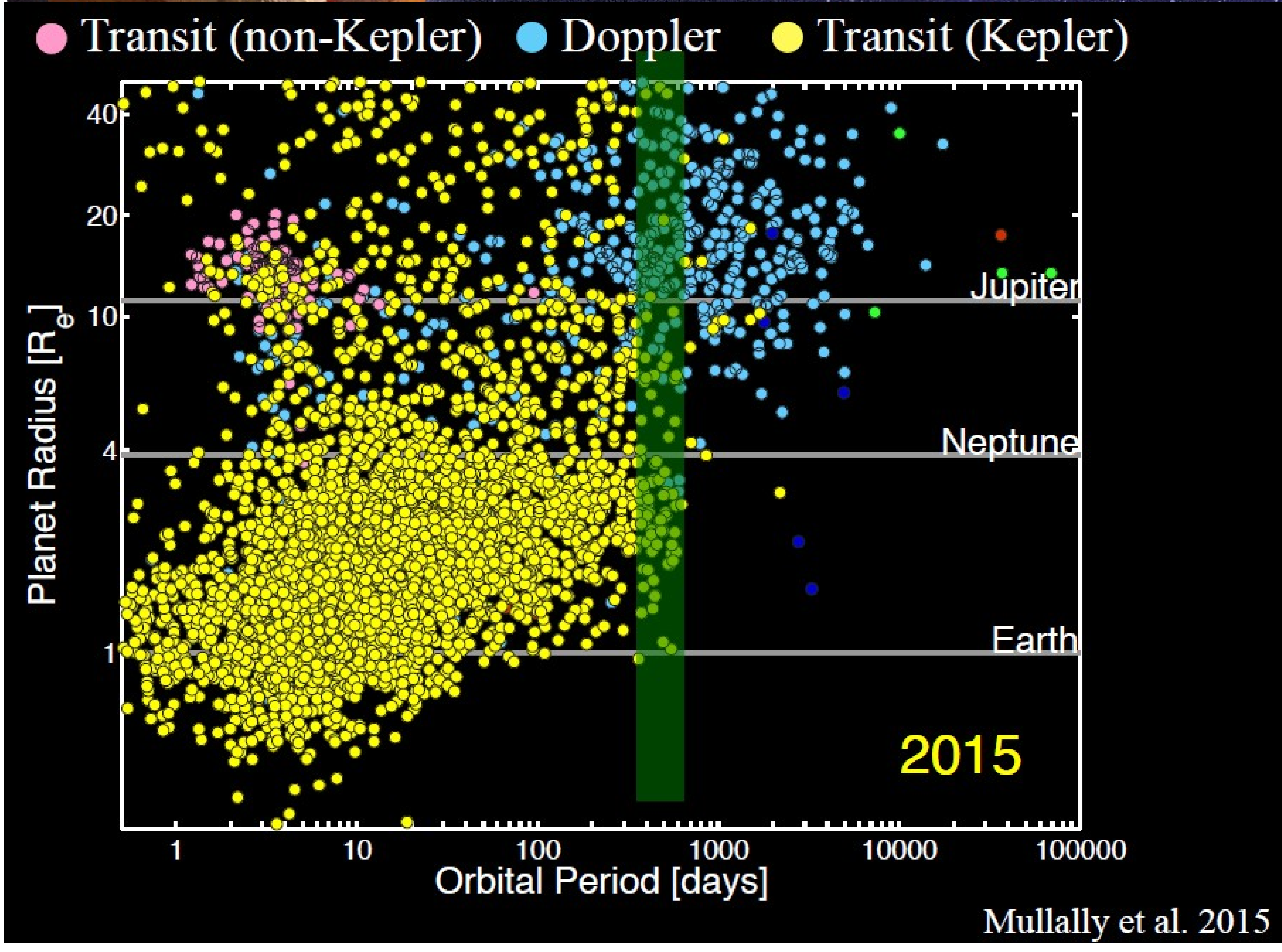


Deleuil et al. 2008

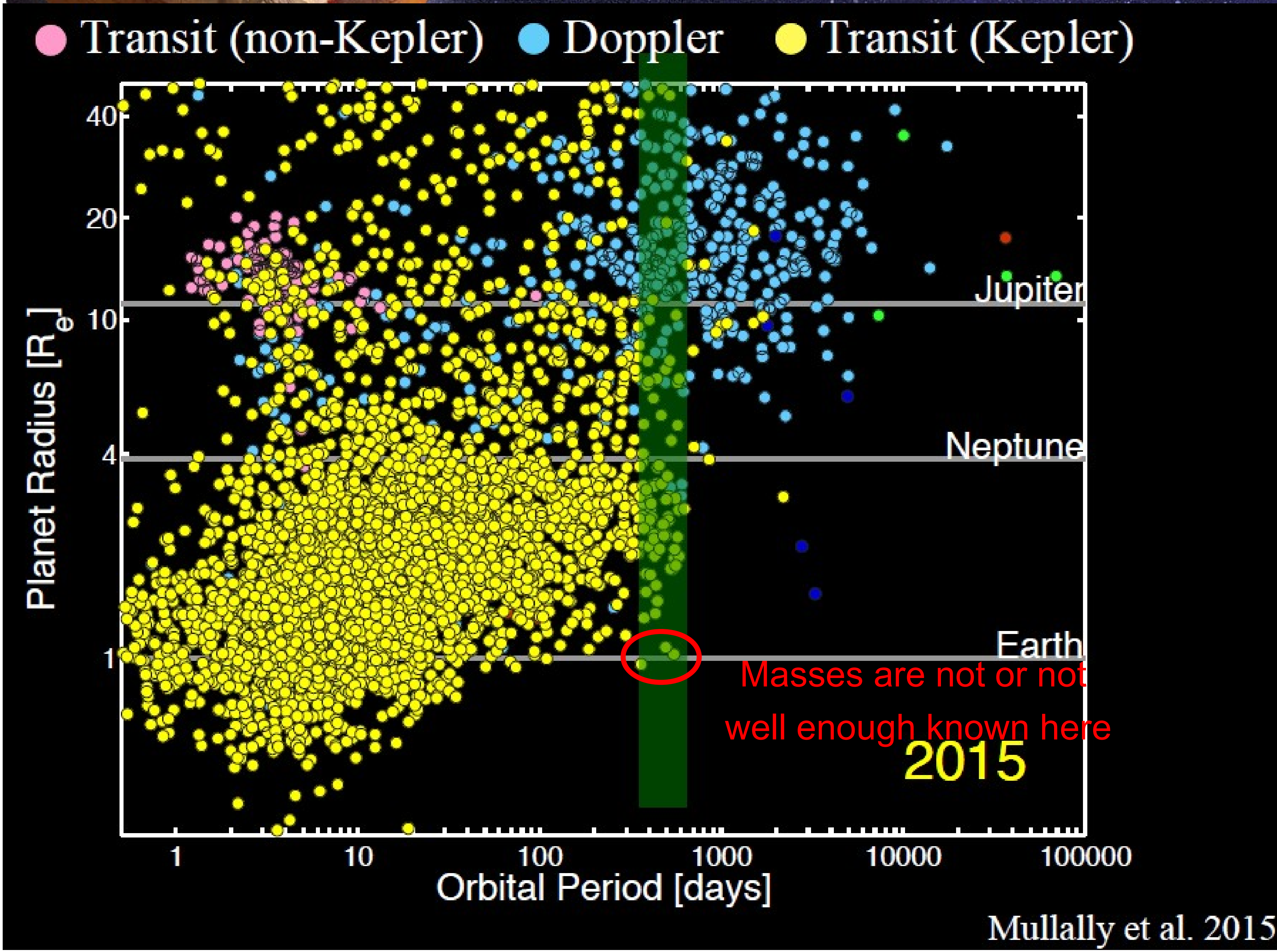
Known planets

In solar system:	8
Discovery by spectroscopy/astrometry:	611 (457 system)
All transiting planet:	1216 (684 system)
Microlensing:	40 (38 system)
Direct imaging:	60 (55 system)
TTV:	23 (14 system)
Total:	1958 planets

+ about ~2000 Kepler-candidates (published)
and ca. 600 CoRoT-candidates (unpublished)

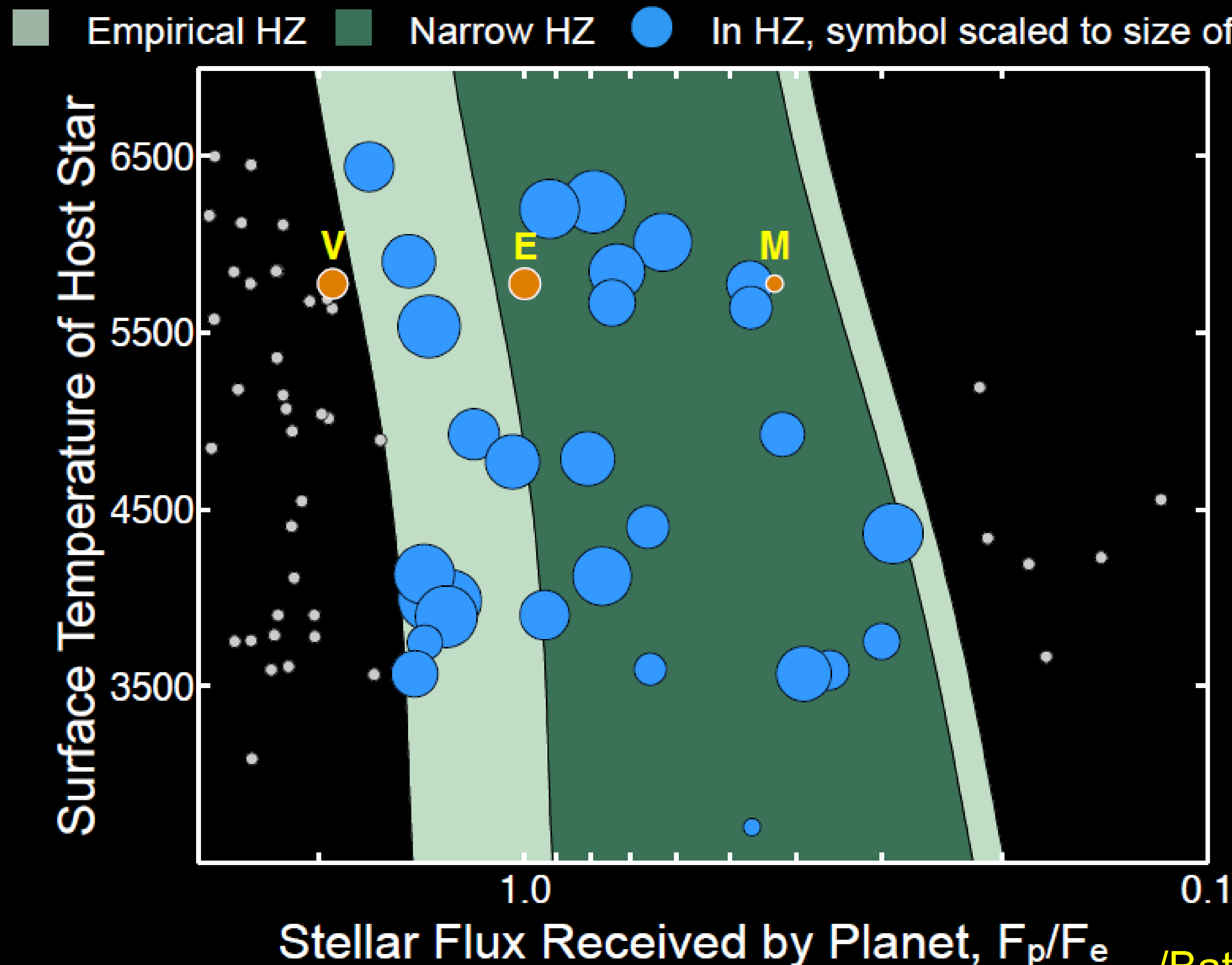


Transit (non-Kepler)
Doppler
Transit (Kepler)
Planet Radius [R_e]
40
20
10
4
1
Jupiter
Neptune
Earth
2015
1
10
100
1000
10000
100000
Orbital Period [days]
Mullally et al. 2015



Transit (non-Kepler)
Doppler
Transit (Kepler)
Planet Radius [R_e]
40
20
10
4
1
Jupiter
Neptune
Earth
Masses are not or not
well enough known here
2015
1
10
100
1000
10000
100000
Orbital Period [days]
Mullally et al. 2015

Small (< 2 R_e) Planets in the HZ: 4 yr



HZ def'n: Kopparapu et al 2013, updated by Leconte et al 2014

/Batalha 2015/

Number of planetary syetems:

(9 planets: HD 10180, quite uncertain)

8 planets: Solar System

7 planets: 1 system (Kepler-90)

6 planets: 2 systems

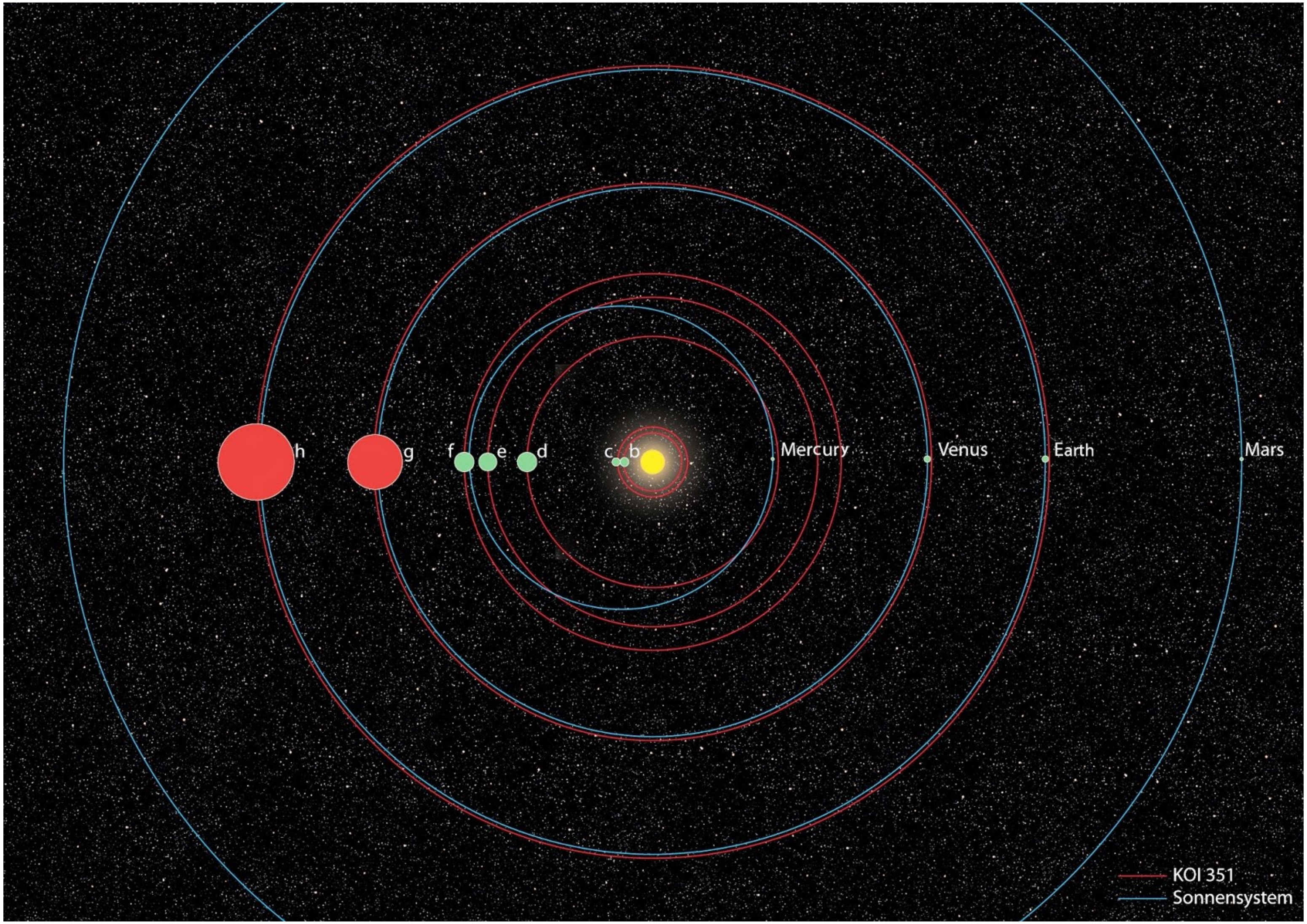
5 planets: 15 system

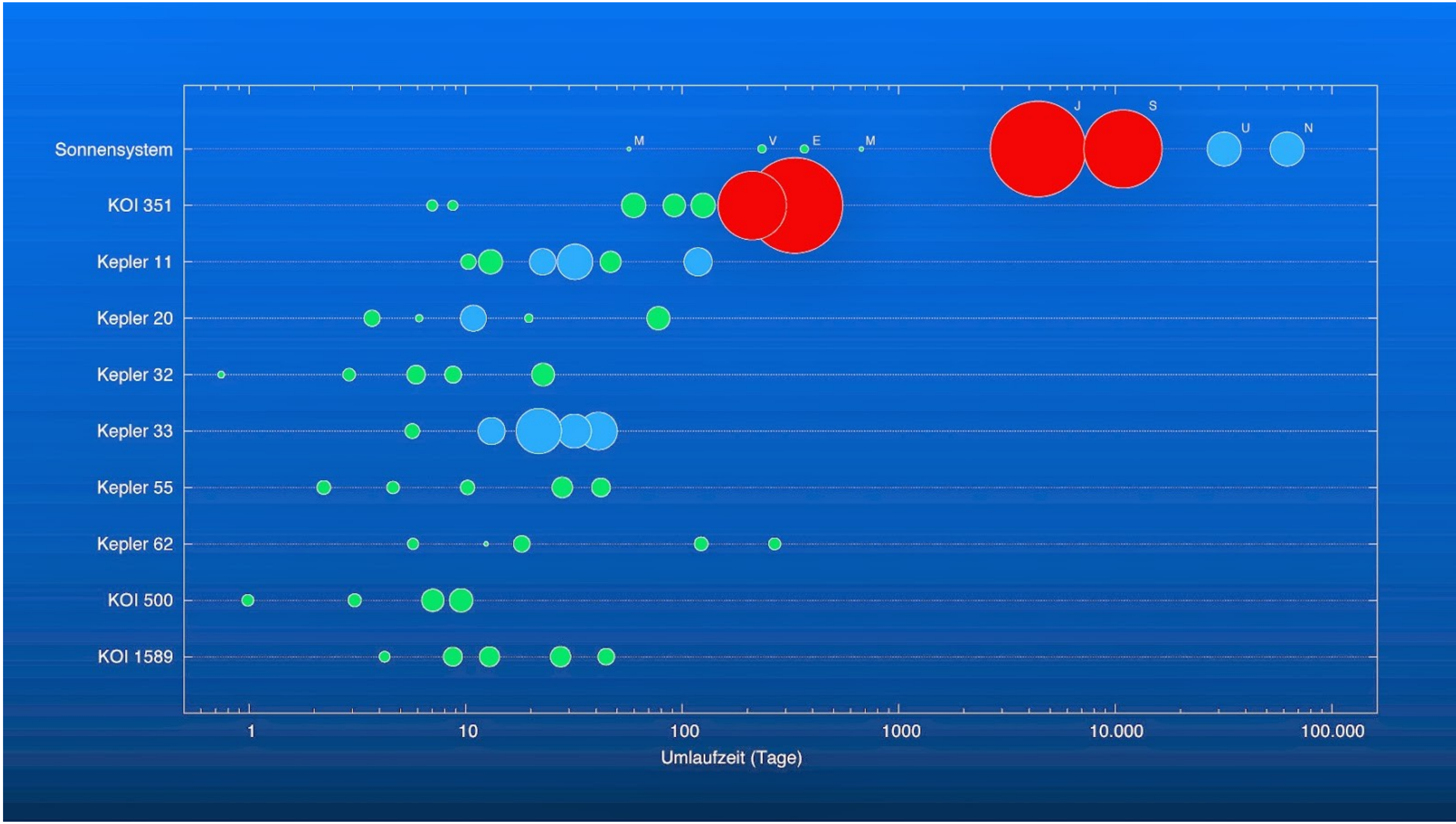
4 planets: 49 system

3 planets: 98 system

2 planets: 300+ system

Kepler-90 (KOI-351)
Cabrera, Csizmadia, Lehmann et al. 2014, ApJ




Sonnensystem
KOI 351
Kepler 11
Kepler 20
Kepler 32
Kepler 33
Kepler 55
Kepler 62
KOI 500
KOI 1589
M
V
E
M
J
S
U
N
1
10
100
1000
10.000
100.000
Umlaufzeit (Tage)

Planets in binary stellar systems:

Circumbinary planets: HW Vir with 2 planets, PSR B1620-26 with one planets

Others: Gamma Cephei; distant stellar companions are relatively frequent

Kepler: about 10 planets around binary stars (triple eclipses)

Extremeties

Smallest planet: PSR 1257 12b 0.02 M_E

Kepler-37b, 0.3 R_E ,

1.7 R_E (CoRoT-7b)

Largest planet: 21.6 M_J (CoRoT-3b), PZ Tel b 62 M_J

ROXs 428b 2.5 R_J (TrES-4 1.7 R_J)

Shortest orbital period: PSR 1719-14b 0.07 days,

0.85 days (CoRoT-7b)

Longest orbital period: 876 yr (Fomalhaut b)

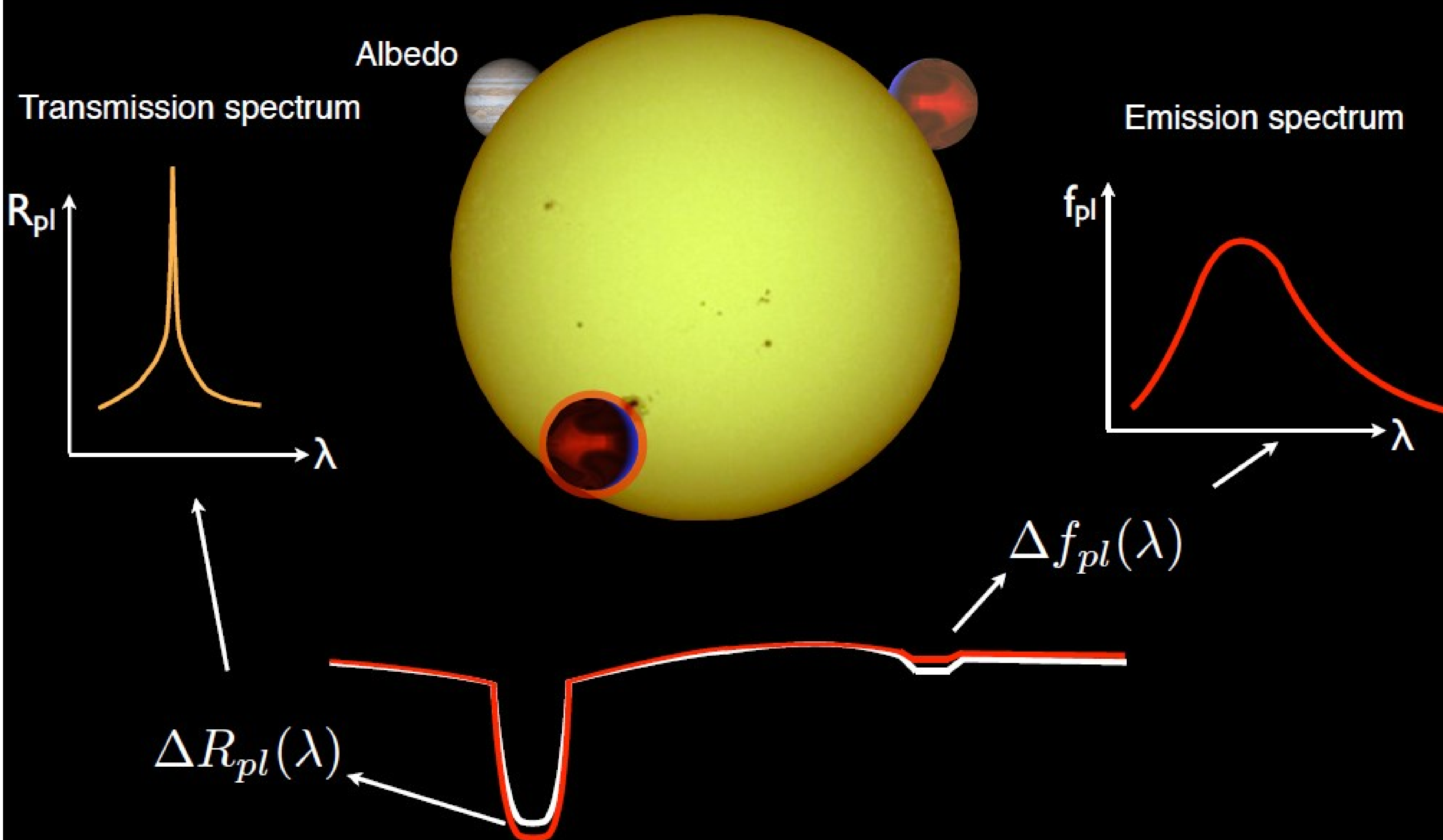
1998 years Oph 11b

Smallest density: 0.13 g/cm^3

Largest eccentricity: ~0.98 (VB 10b)

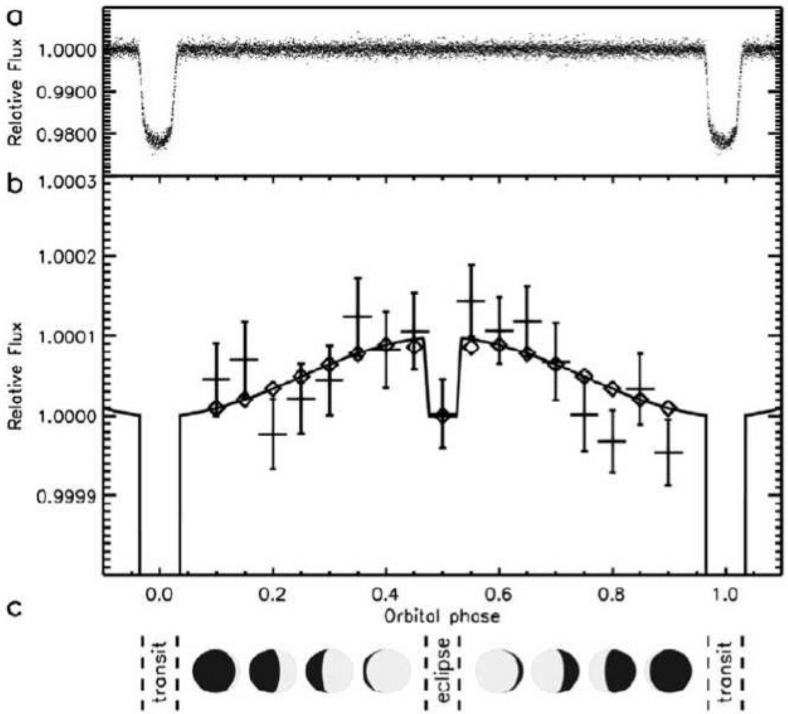
5. Occultations, phase curves, atmospheres, composition...

Transiting Exoplanet Spectra

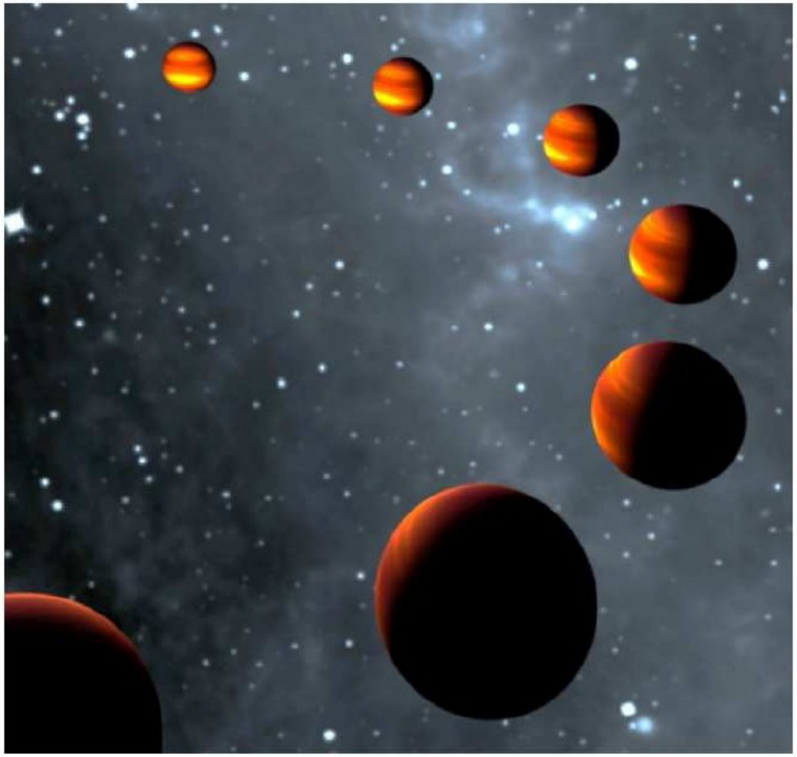


The secondary eclipse

at optical wavelengths with CoRoT: CoRoT-1b



(Snellen et al. 2009)



CoRoT-1b: the secondary transit

The secondary transit:

observed from space (CoRoT)

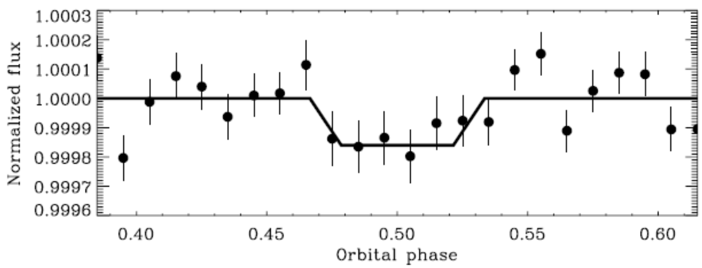


Fig. 4. Phase folded curve of CoRoT-1b during the phases of secondary eclipse. The data have been binned in 0.01 in phase (~22 min)

Alonso et al. (2009) A&A, submitted

see also Snellen et al. (2009) Nature, 459, 543

T=2330K (+120/-140)

e cos w<0.014

observed from ground (VLT)

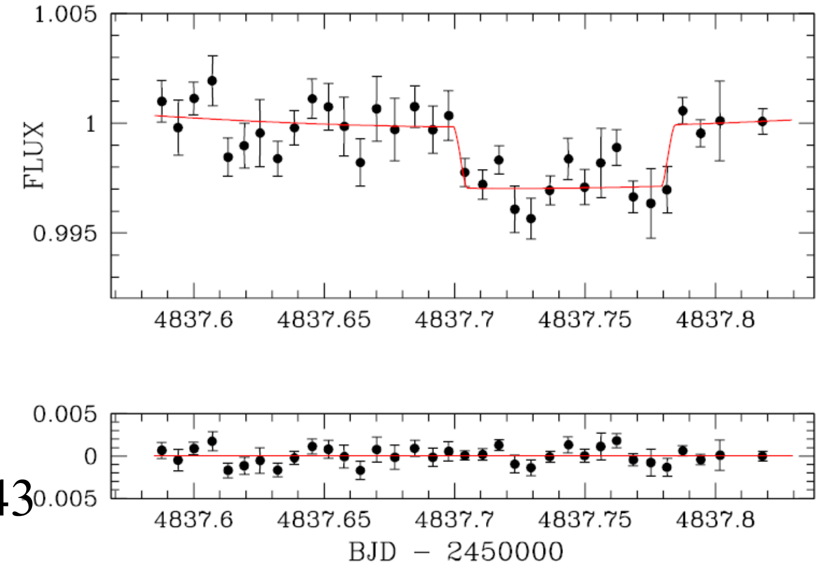
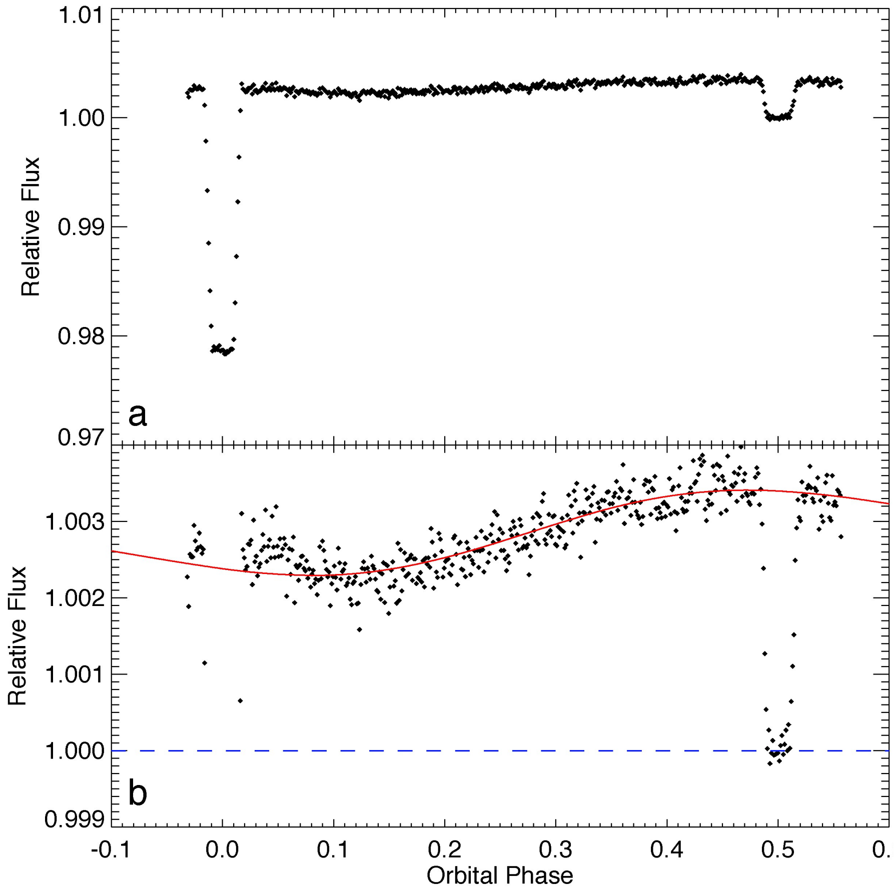


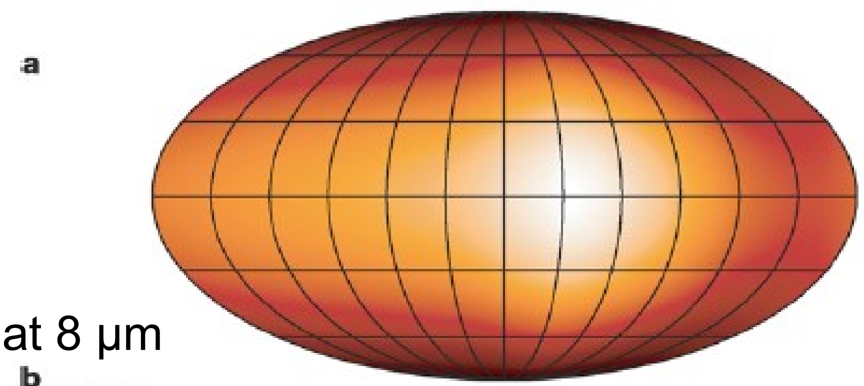
Fig. 2. *Top*: VLT/HAWK-I 2.09 μm occultation light curve binned per 10 minutes, with the best-fitting occultation + trend model superimposed. *Bottom*: residuals of the fit.

Gillon et al. (2009) A&A

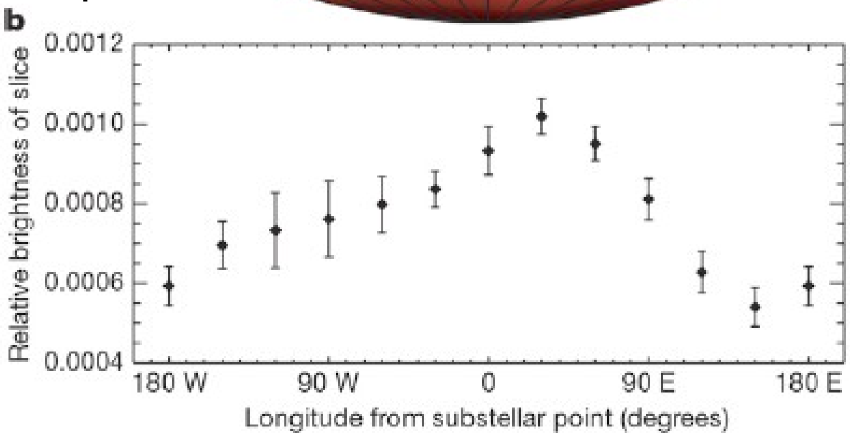
The secondary eclipse

observed with Spitzer in IR: HD189733b





at 8 μm

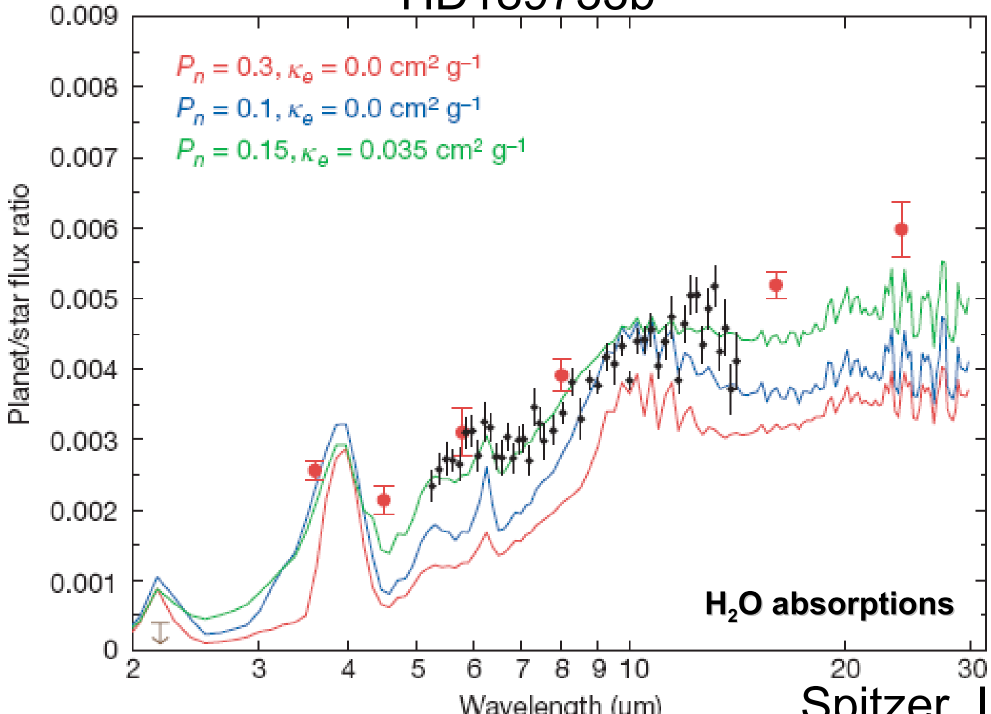


Knutson et al. 2007

Temperature and atmospheric composition

The secondary transit

HD189733b

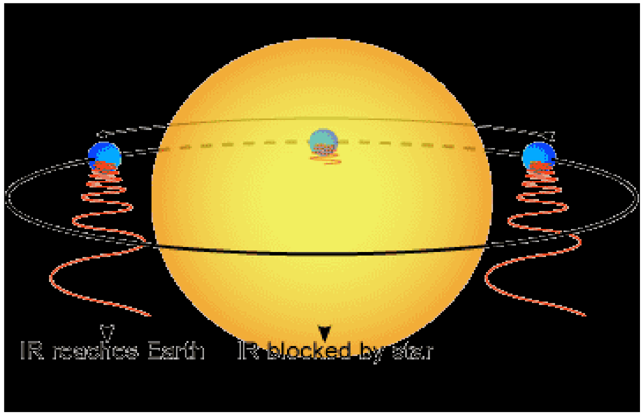


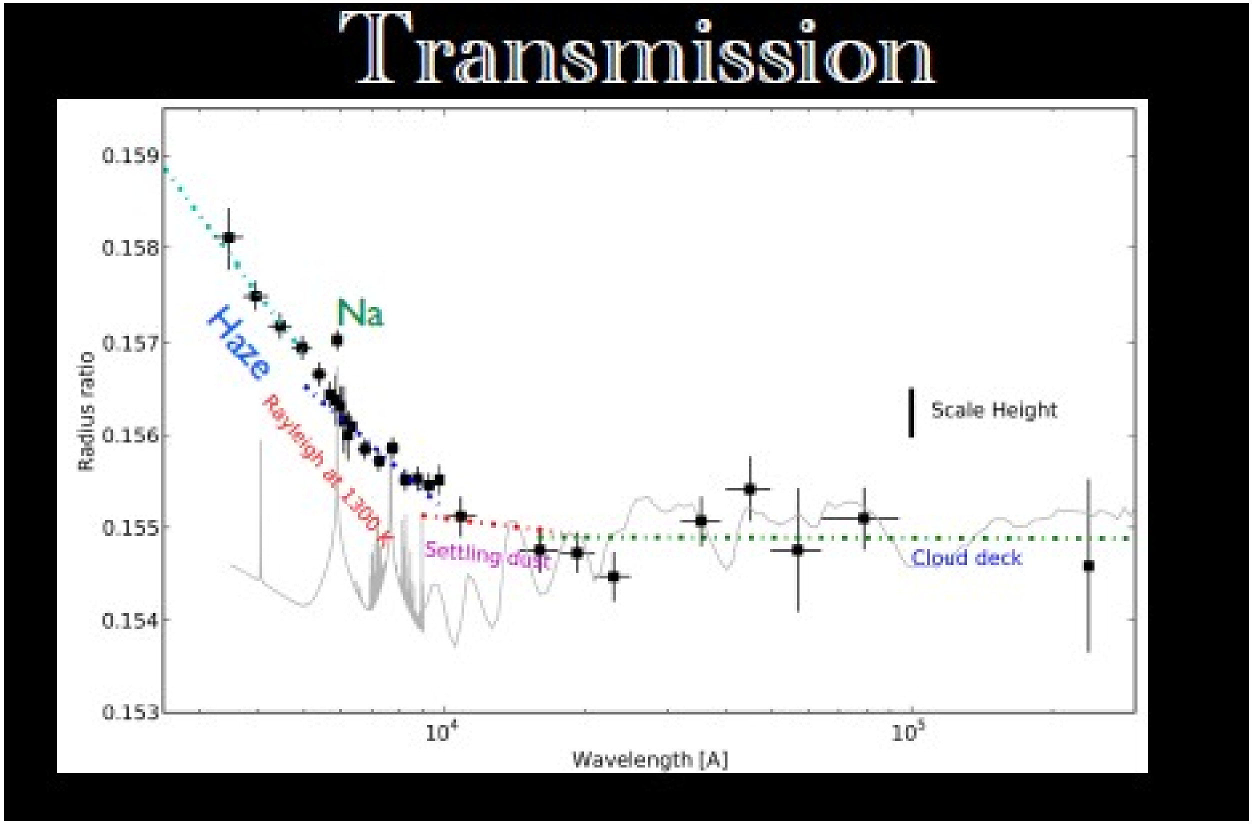
Spitzer, IRS

Grillmair et al. 2008

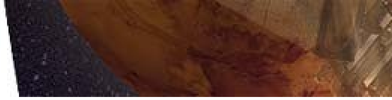
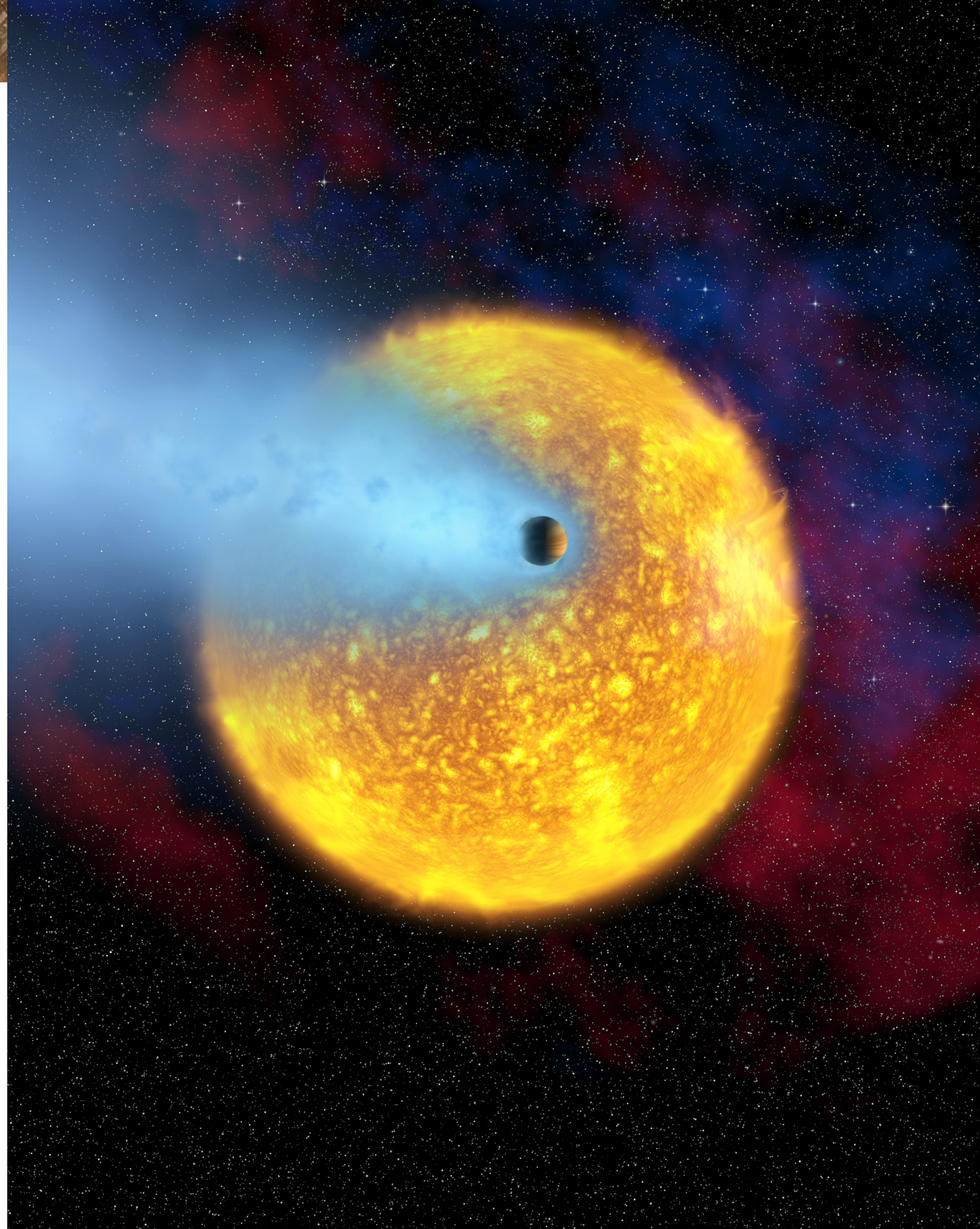
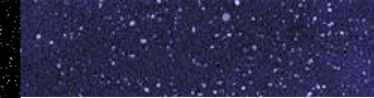
Observations of the secondary eclipse allow us to measure:

- excentricity
- temperature
- emission spectra

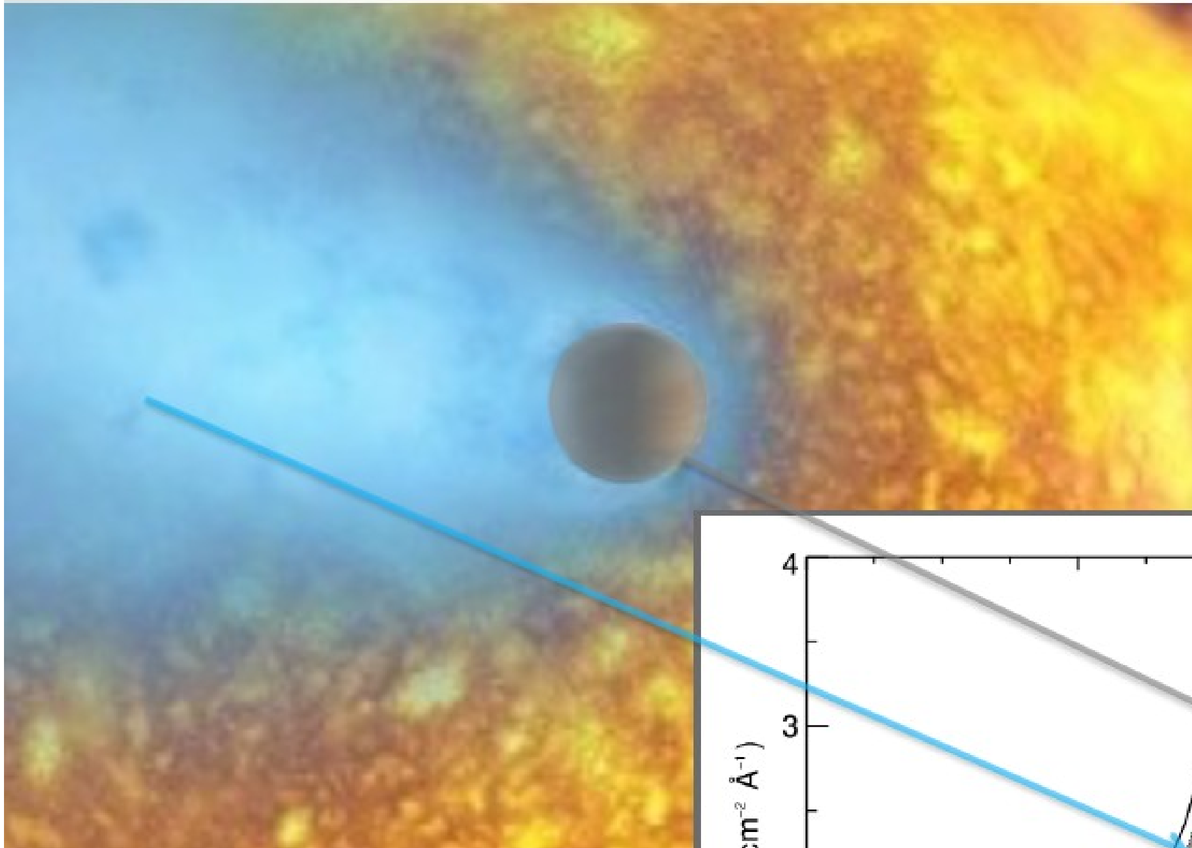




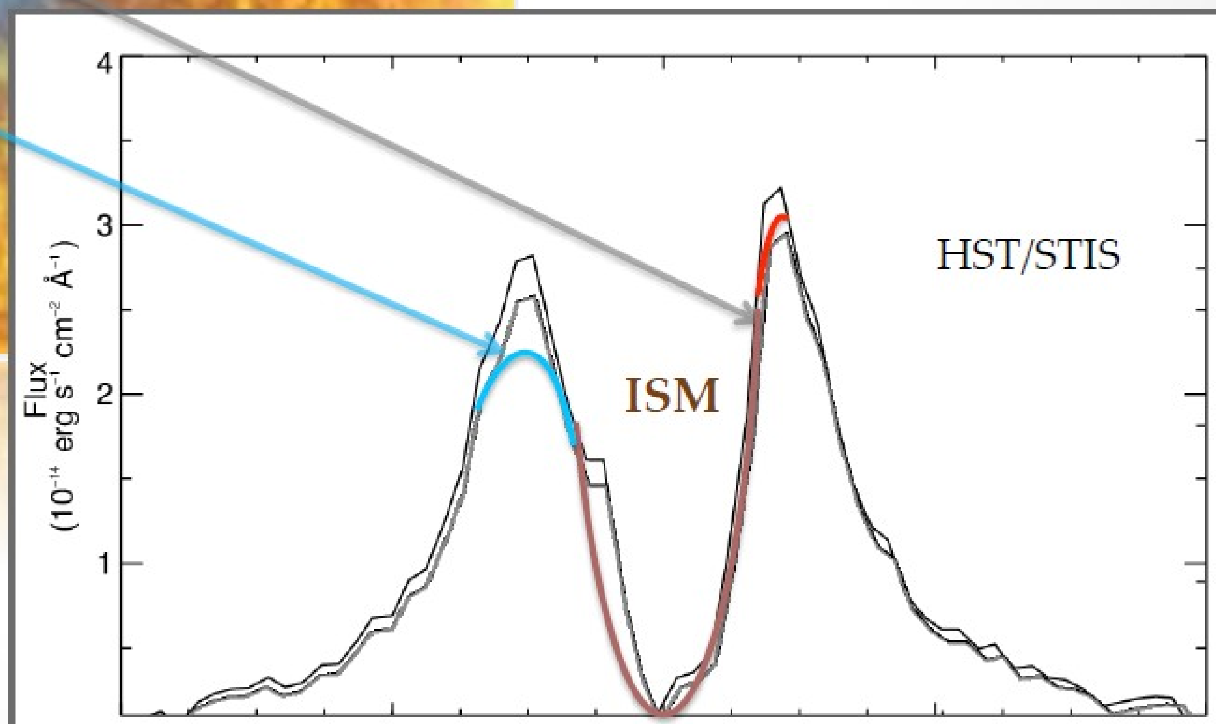
HD 189 733 /Sing 2015/

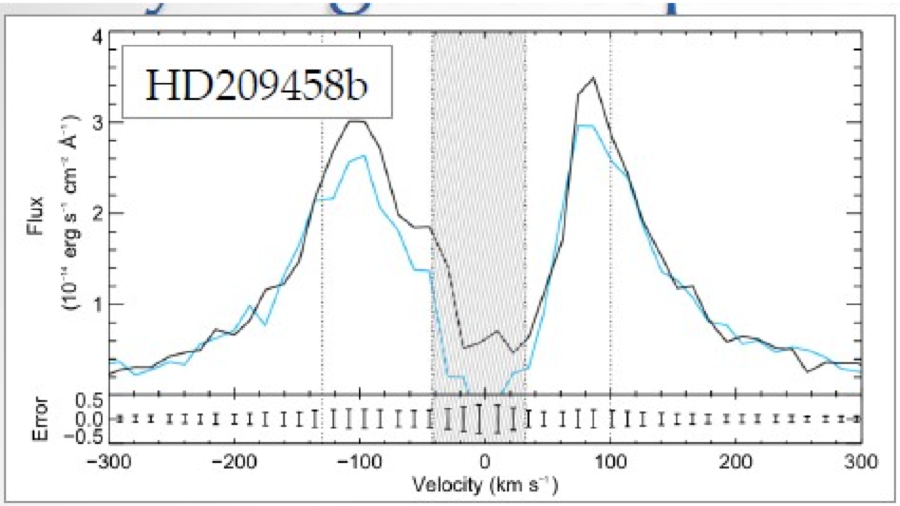




UV transmission spectroscopy of the exosphere



Planetary occultation~ 1%

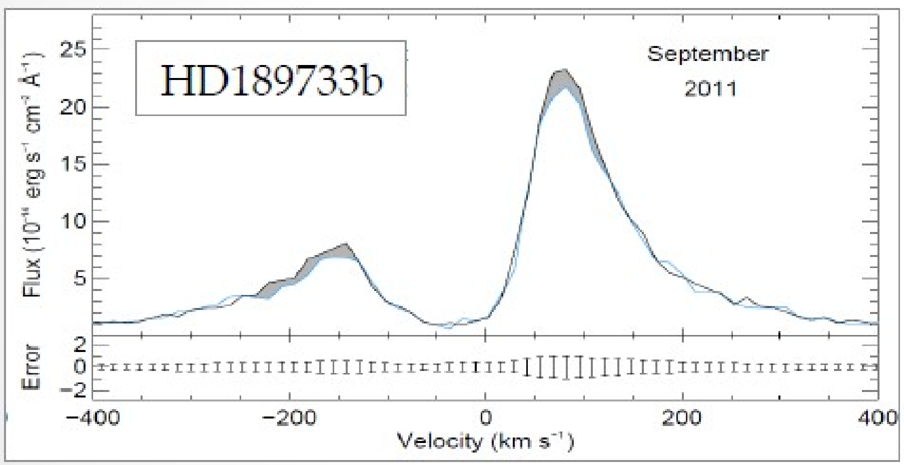




Hot-Jupiter:

15 ± 4 % in [-130 ; -40] km/s

Vidal-Madjar et al. (2003),
Ben-Jaffel (2007, 2008)
Vidal-Madjar et al. (2008)



Hot-Jupiter:

14.4 ± 3,6 % in [-220 ; -140] km/s

Lecavelier, Bourrier et al. 2012

(Exo)moons

Proposed detection methods for moons:

By photometry:

Sartoretti & Schneider 1999 (A&AS 134, 553)

Szabó et al. 2006 (A&A 450, 395)

By TTV:

Simon et al. 2007 (A&A 470, 727)

Kipping 2009ab (MNRAS 392, 181, MNRAS 396, 1797)

By Rossiter-McLaughlin effect:

Simon et al., 2009 (EM&P accepted)

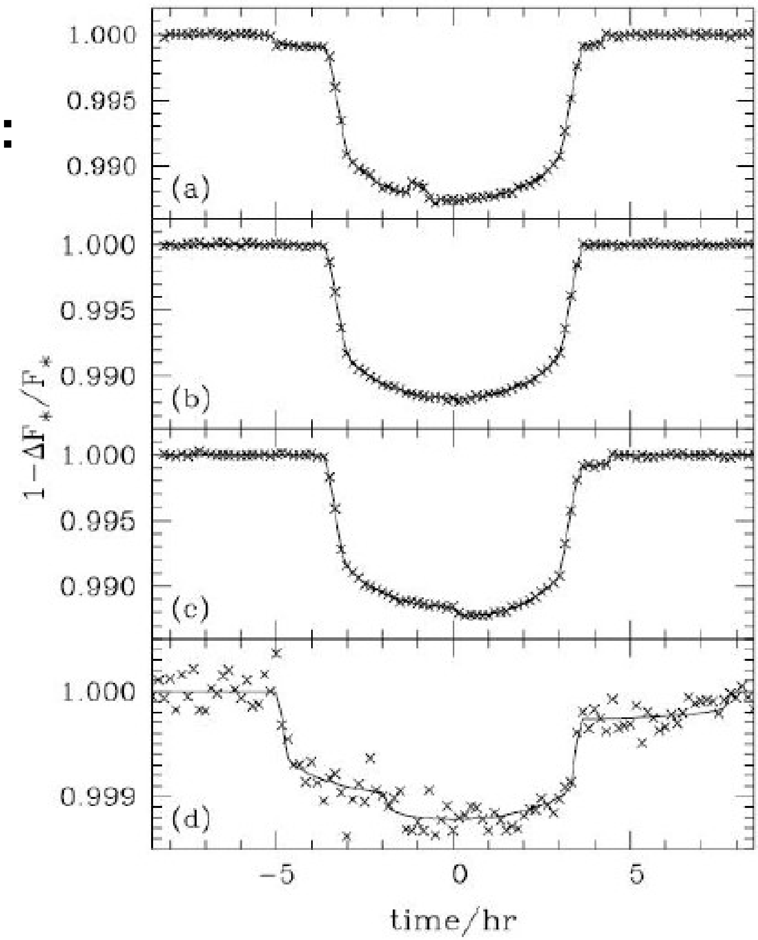
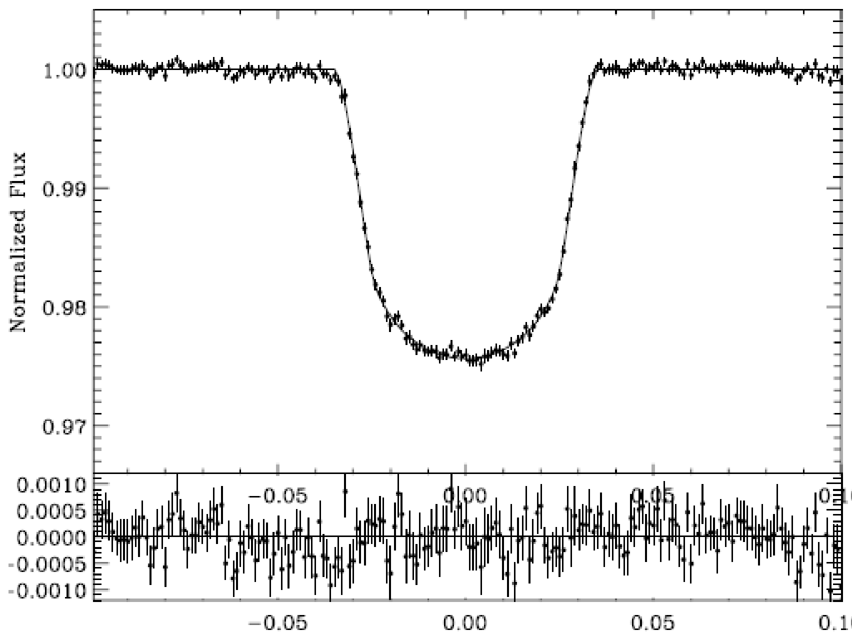
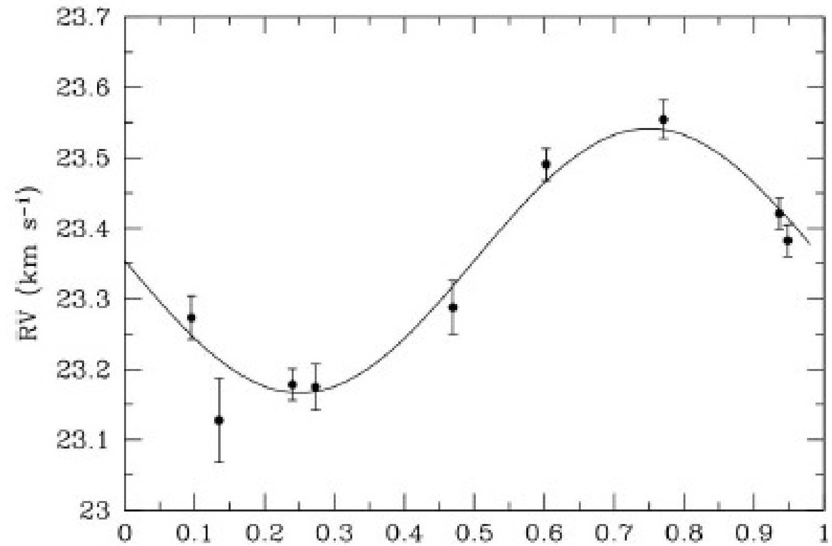


Figure 12: Possible transit shapes for a planet-moon system (Sartoretti and Schneider (1999)); For detailed explanation see text. Note that in (d) the scale is different.

CoRoT-1b: first exoplanet discovery from space





The planet:

Period: 1.5 days

Radius: 1.47+/-0.06 R_{Jup}

Mass: 0.99+/-0.09 M_{Jup}

The star:

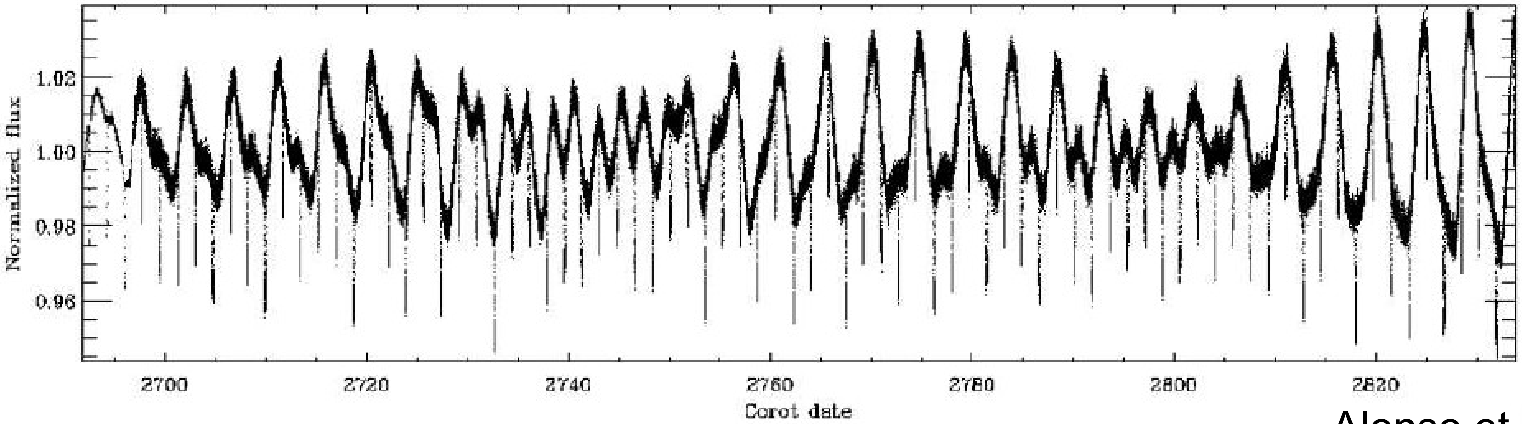
Type: G0V

Magnitude: V = 13.6 mag

Mass: 0.9 M_{sun}

(Barge et al. 2008)

The star as source of noise
Example: CoRoT-2b



Alonso et al. 2008

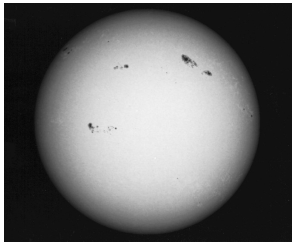
- Observations made during the first „long run“ of CoRoT of 152 days duration

- ~369000 flux measurements with 512 s (1. week) and then 32 s sampling

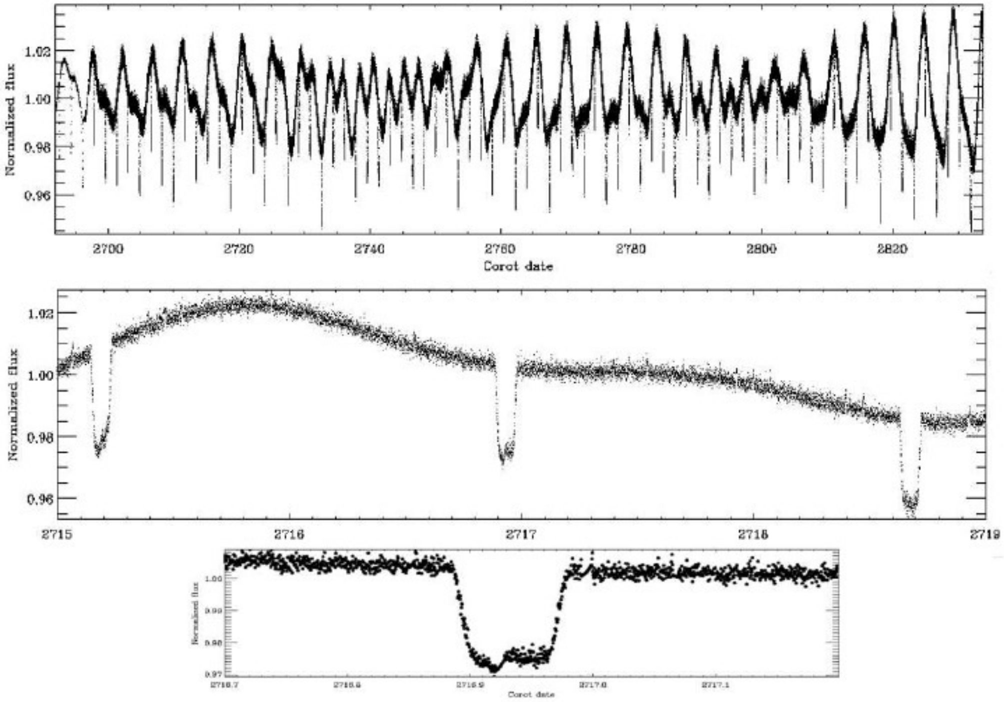
→The star shows periodic variation over several days due to surface spots with an amplitude of 6%

→ One of the major noise sources is stellar variability!

Effects of stellar spots

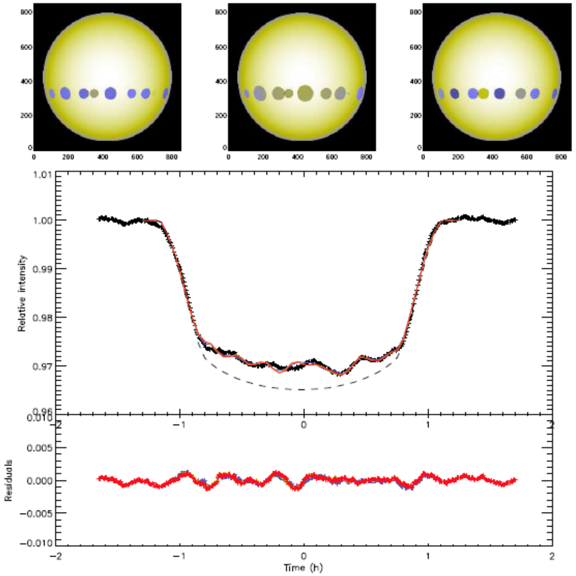


The effect of stellar activity on the shape transits:



Alonso et al. (2009) IAUS 253, 91

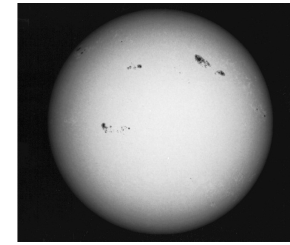
see also Czesla et al. (2009) A&A

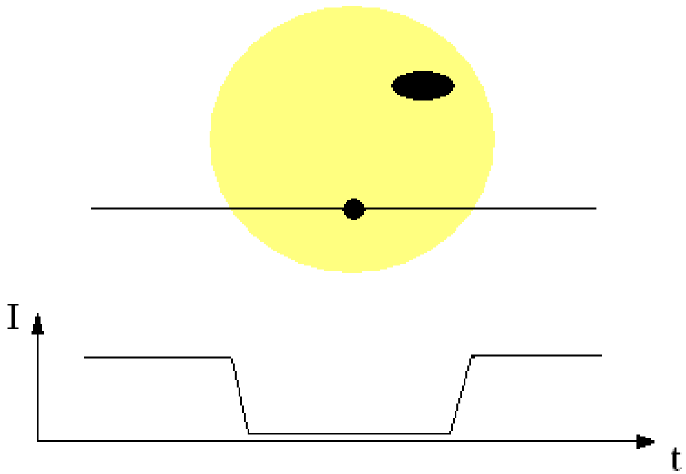


Examples of stellar models to fit individual transit shapes-

Silva et al. (2009) A&A

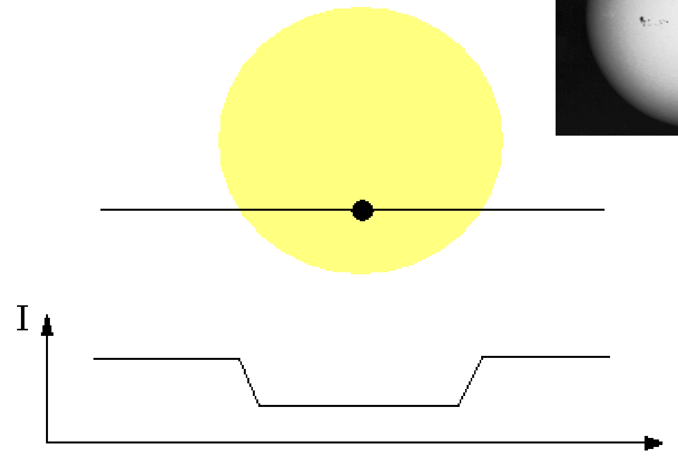
Effects of stellar spots





$$DF = (R_p/R_s)^2 F_0$$

$$F_{star} = F_0 - F_{spot}$$



$$DF = (R_p/R_s)^2 F_0$$

$$F_{star} = F_0$$

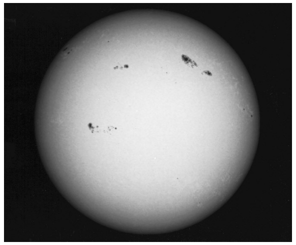
$$\frac{DF}{F_{star}} = \frac{DF}{F_0 - F_{spot}} > \frac{DF}{F_{star}} = \frac{DF}{F_0}$$

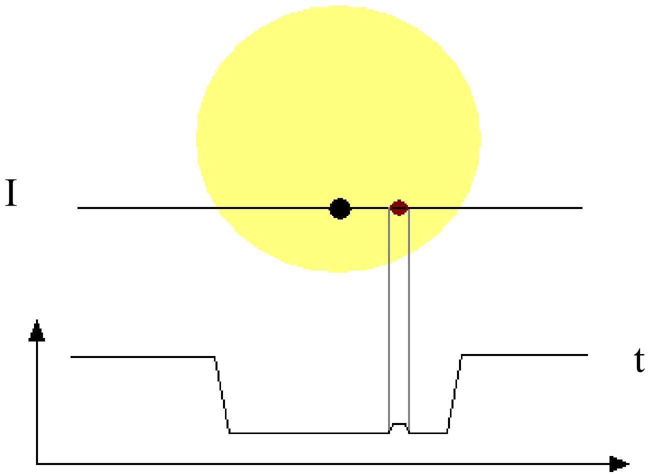
- spotted star: fainter, baseline lower.
- unspotted star: brighter, baseline higher.
- light loss due to planet transit is the same.

→ after normalization: different depths...

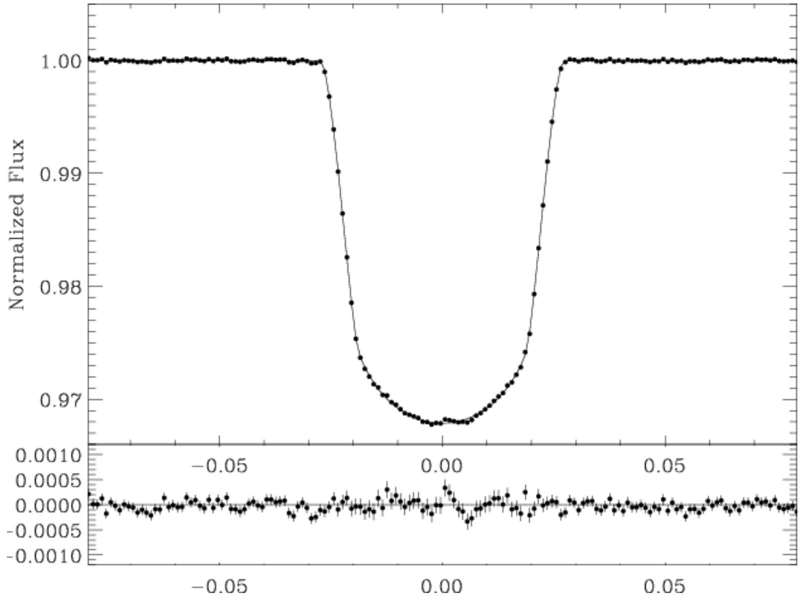
→ can cause systematic errors in planet radii.

Effects of stellar spots





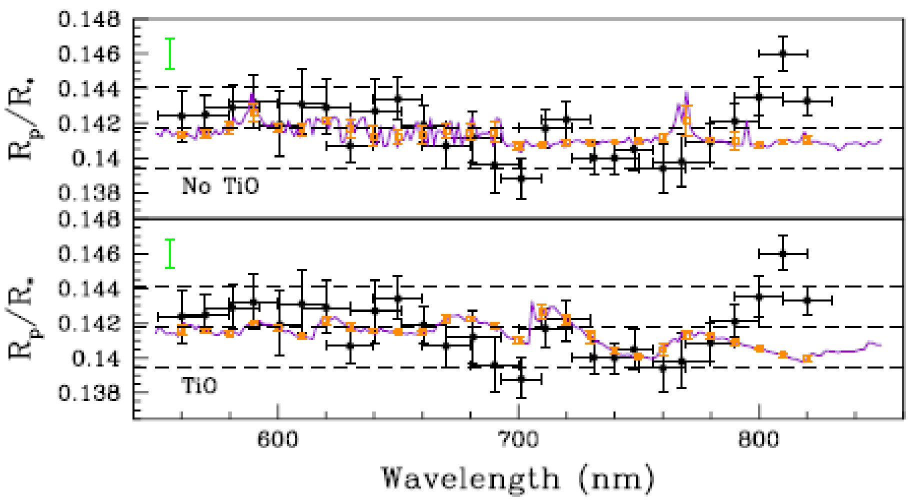
CoRoT-2b



Alonso et al. 2008

When the planet moves in front of a small spot and covers it, the star becomes brighter for the observer: we see a bump.

Atmospheric study and spot of WASP-19 by VLT-FORS2



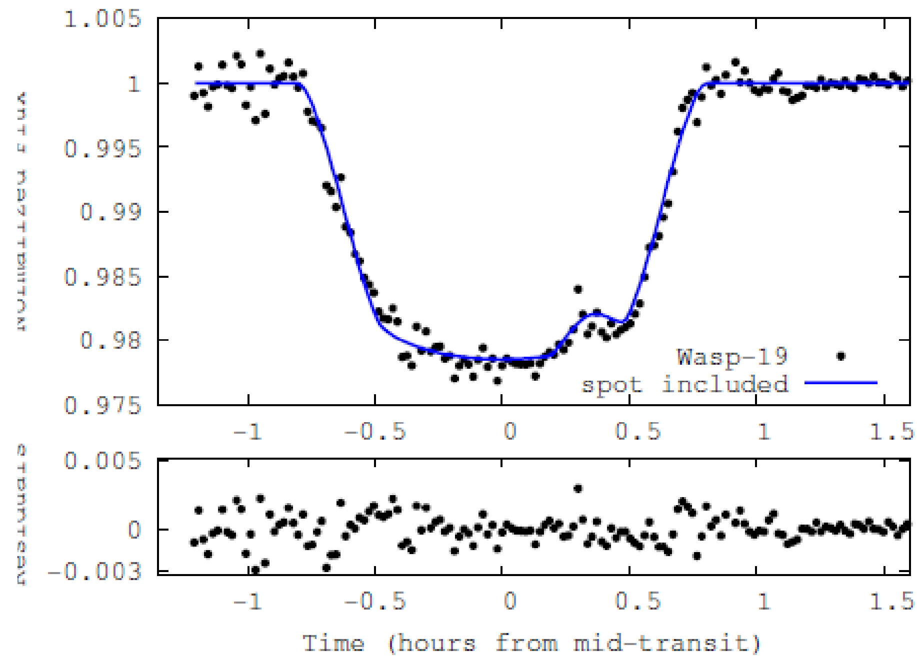
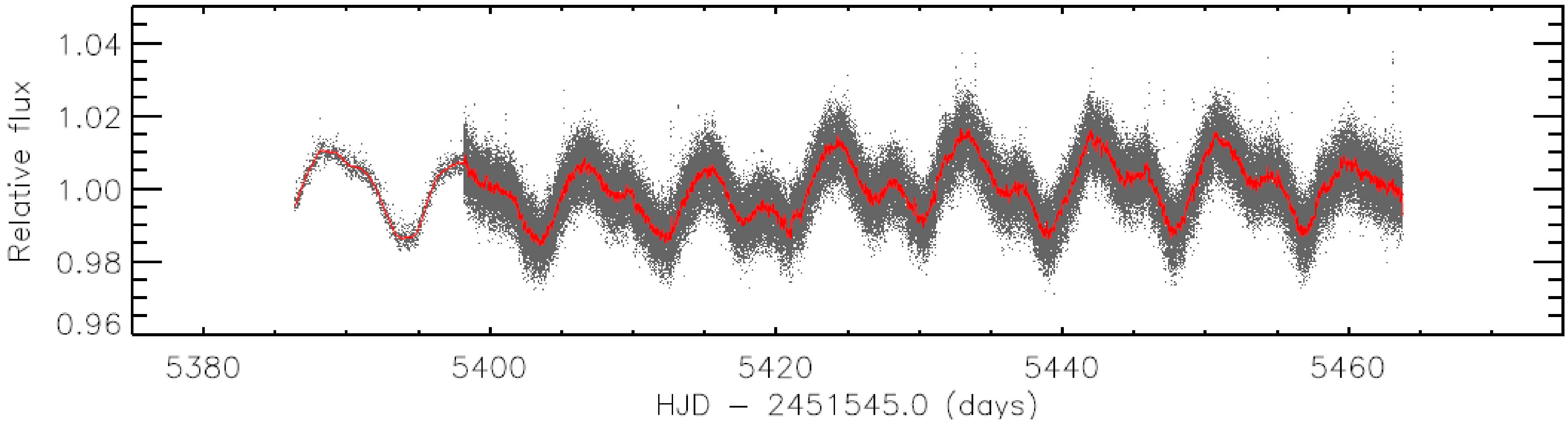


Fig. A.5. Broadband (white) light curve modelled with the GEMC+PRISM code for the purpose of stellar spot characterization, values for which are shown in Table A.2.

Sedaghati, E.; Boffin, H. M. J.; Csizmadia, Sz.; Gibson, N.; Kabath, P.; Mallonn, M.; Van den Ancker, M. E., 2015, A&A



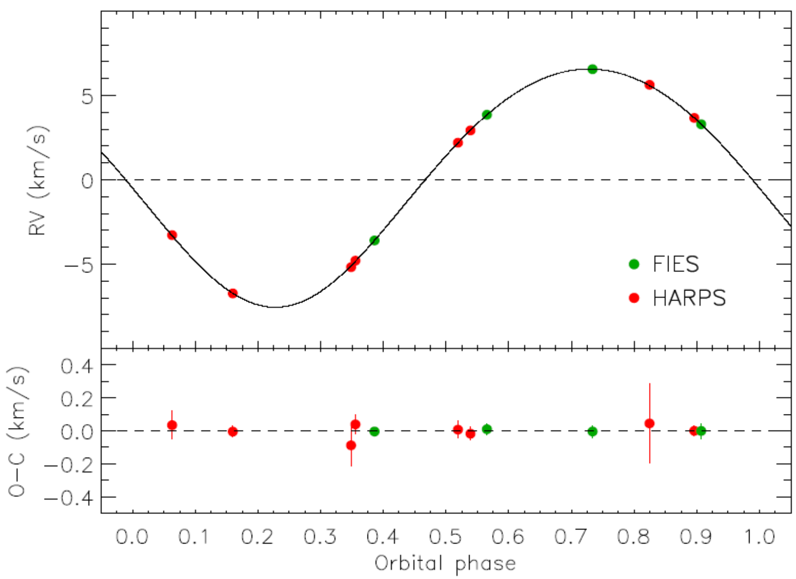
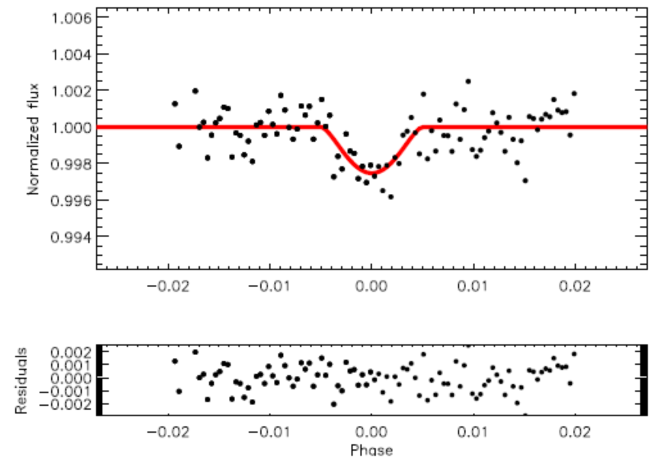


Fig. 3. Upper panel: Phase-folded RV measurements of CoRoT-33. Red circles represent the HARPS-measurements while green circles do the data points obtained by FIES-instrument. Black solid line represents the eccentric orbit fit. The RV points and the fit is shifted by the γ-velocity of the system. Lower panel: it shows the residuals of the fit. Vertical lines on the data points indicate their error bars.



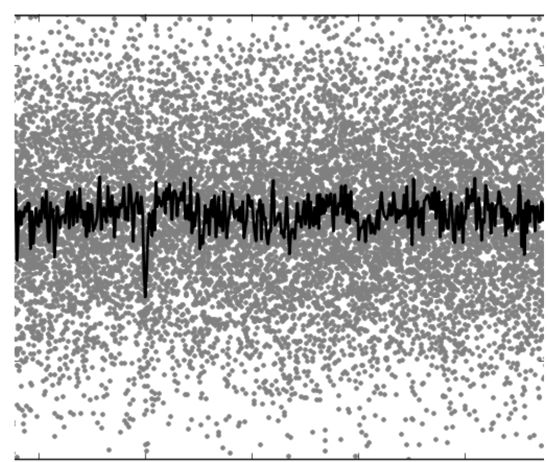
2.8 mmag,

1.4 hours long

transit on an

R=14.3 mag

star



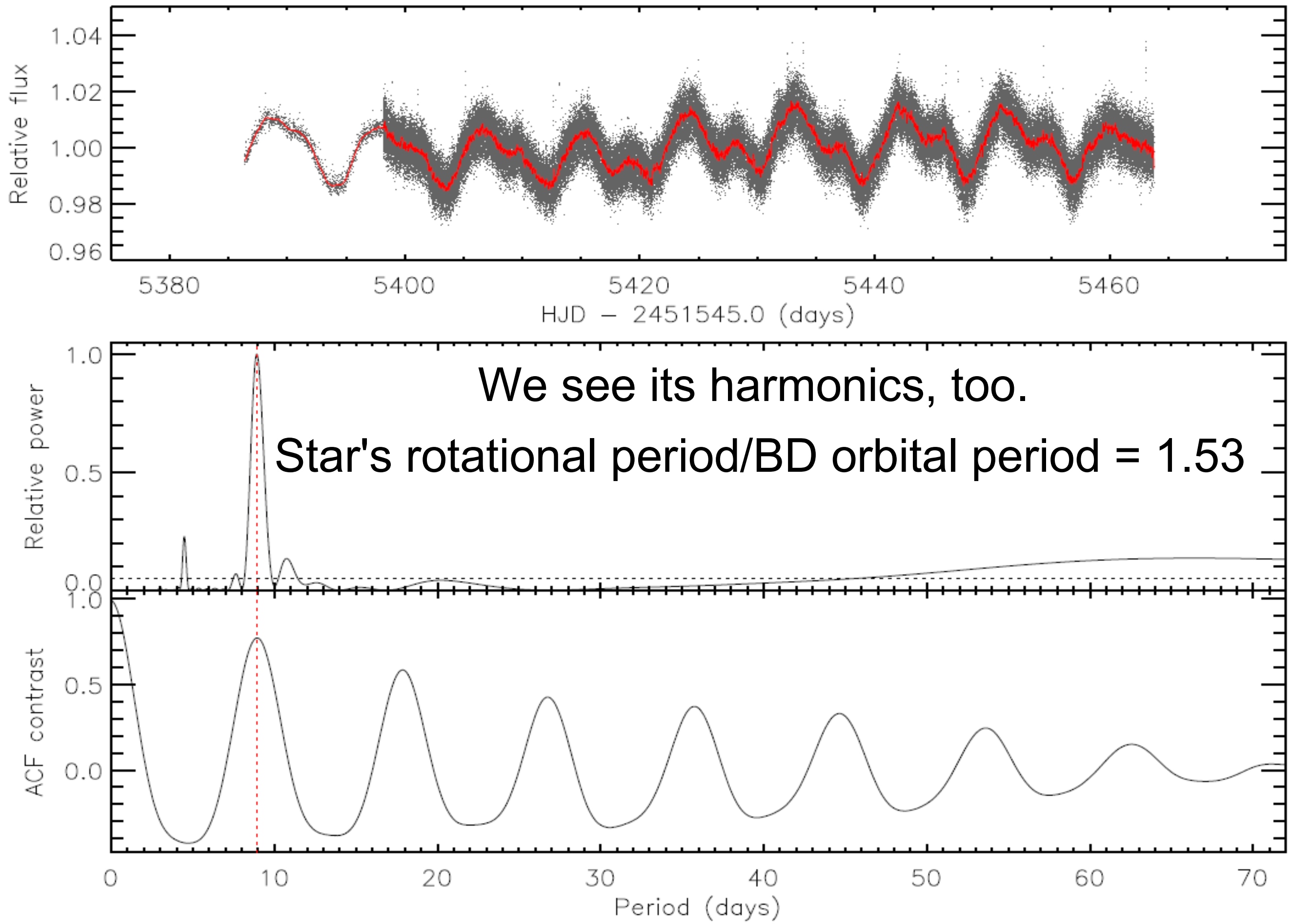


Fig. 1. *Upper panel*. Full CoRoT light curve of CoRoT-33. The grey points represent the median-normalized raw data points after a 5-point width median filtering. Only data points with flag "0" have been used for this curve. The red line is a convolution of the raw light curve with a Savitzky-Golay filter that enhances the light curve variations. Flux is normalized to the median of all flux values. *Middle panel*. Lomb-Scargle periodogram of the light curve of CoRoT-33. The horizontal dashed line denotes the 0.01 % false-alarm probability. The vertical red line marks the rotation period of the star. *Lower panel*. Autocorrelation function (ACF) of light curve, following the subtraction of the best fitting transit model. The red dashed line marks the peak corresponding to the rotation period of CoRoT-33 (see Section 3.4)

Béky et al. (2014, ApJ and references thereof), hot Jupiters:

HAT-P-11	1:6
Kepler-17b:	1:12
CoRoT-2b:	5:13
CoRoT-4b:	1:1
Kepler-13b:	3:5
Tau Boo:	1:1

Csizmadia et al. (2015, in press, A&A), brown dwarf:

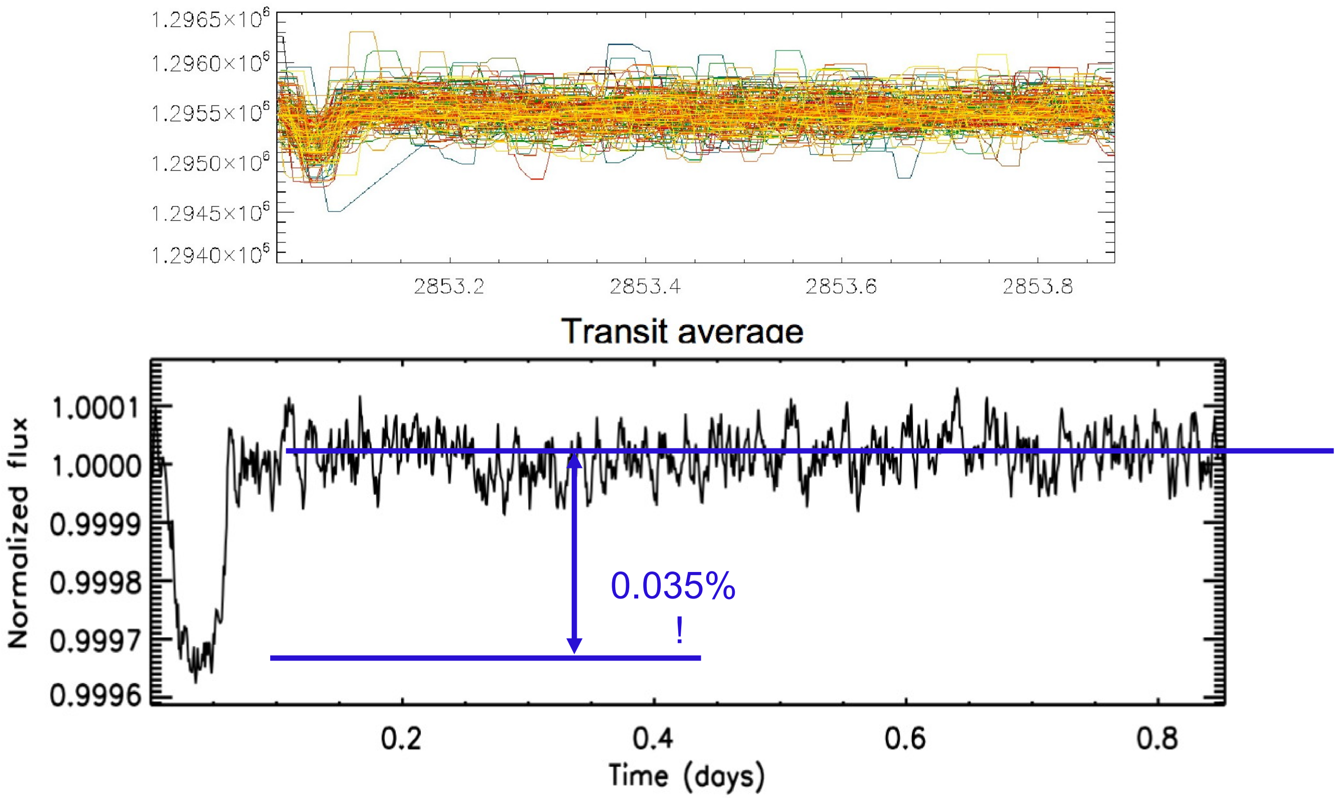
CoRoT-33b 2:3

Eigmüller et al. (2015, subm.), F+dM binary:

BEST-C2 1:2

Many binary stars: 1:1

CoRoT-7b: The folded light curve



- short period : P= 0.8536 days

➜ transit depth : $\Delta F/F = 0.035\%$

Comparison to HAT-P11b, smallest depth ever observed from ground

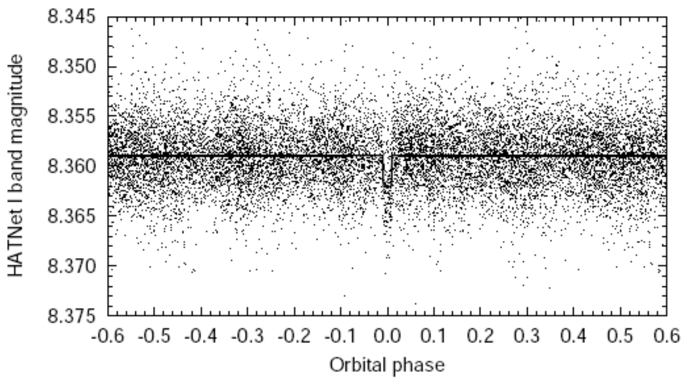


FIG. 1.— The HATNet discovery light curve of HAT-P-11 exhibiting 11470 individual measurements at 5.5 min cadence. The unbinned instrumental I-band photometry was obtained with the HAT-6 (Arizona) and HAT-9 (Hawaii) telescopes of HATNet (see text for details), and folded with the period of $P = 4.8878162$ days, which is the result of the global fit described in § 5. Zero orbital phase corresponds to the center of the transit. Superimposed is the so-called "P1P3" analytic model that was used to describe the HATNet data (an approximation of the Mandel & Agol (2002) analytic formulae; see § 5.1).

Bakos et al. 2009 ApJ

Planet:

P: 4.8878162 days

Mass: 25.8 M⊕

Radius: 0.422 R_J (4.7 R_{earth})

Star: K4 dwarf

V: 9.587 mag

$M_\star = 0.809\ M_S$

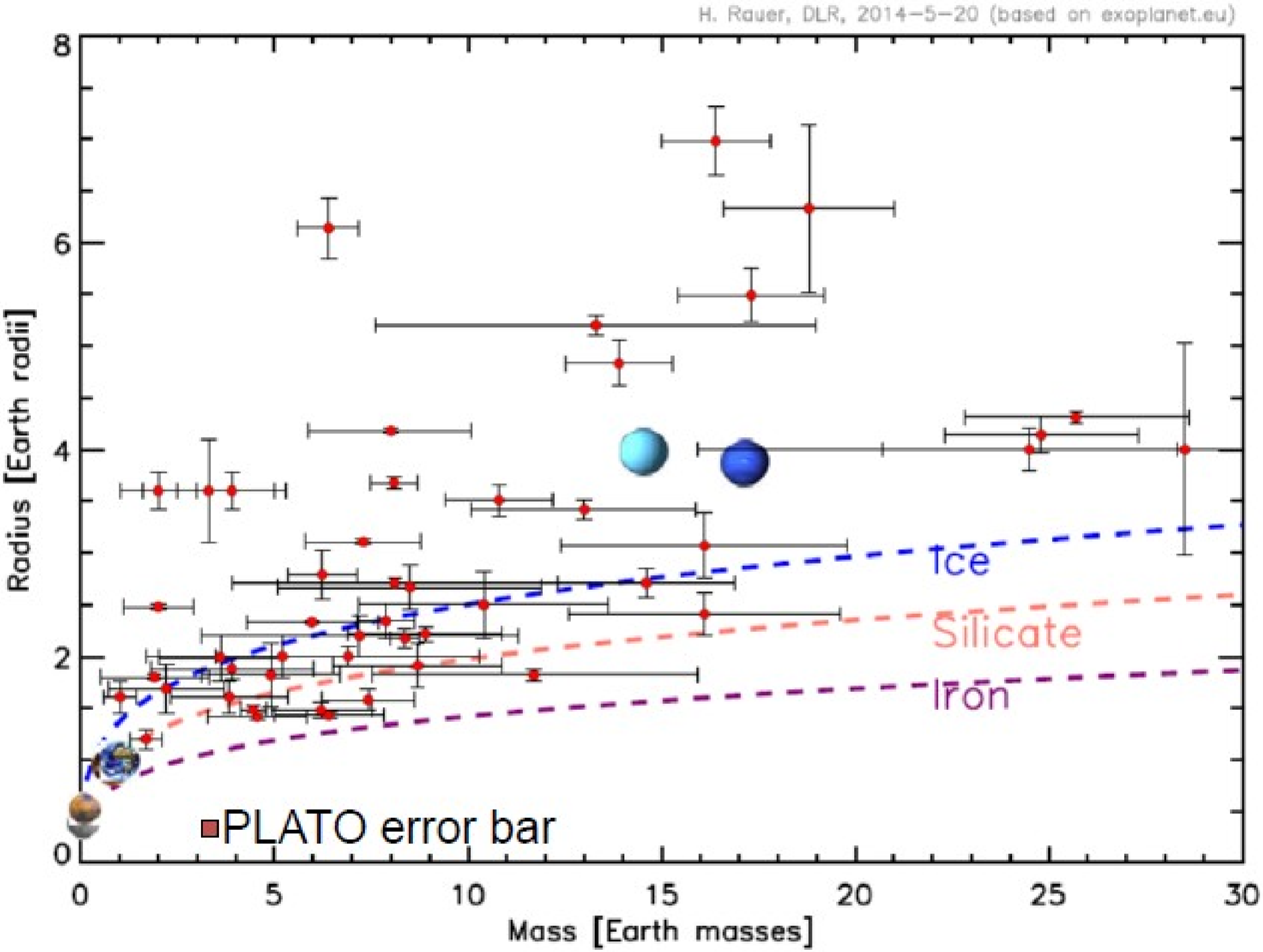
$R_\star = 0.752\ R_S$

The depth of HAT-P-11b is 4.2 mmag, which is a very challenging measurement from ground.

To be compared to the depth of CoRoT-7b which is 0.4 mmag (size below $2R_E$)

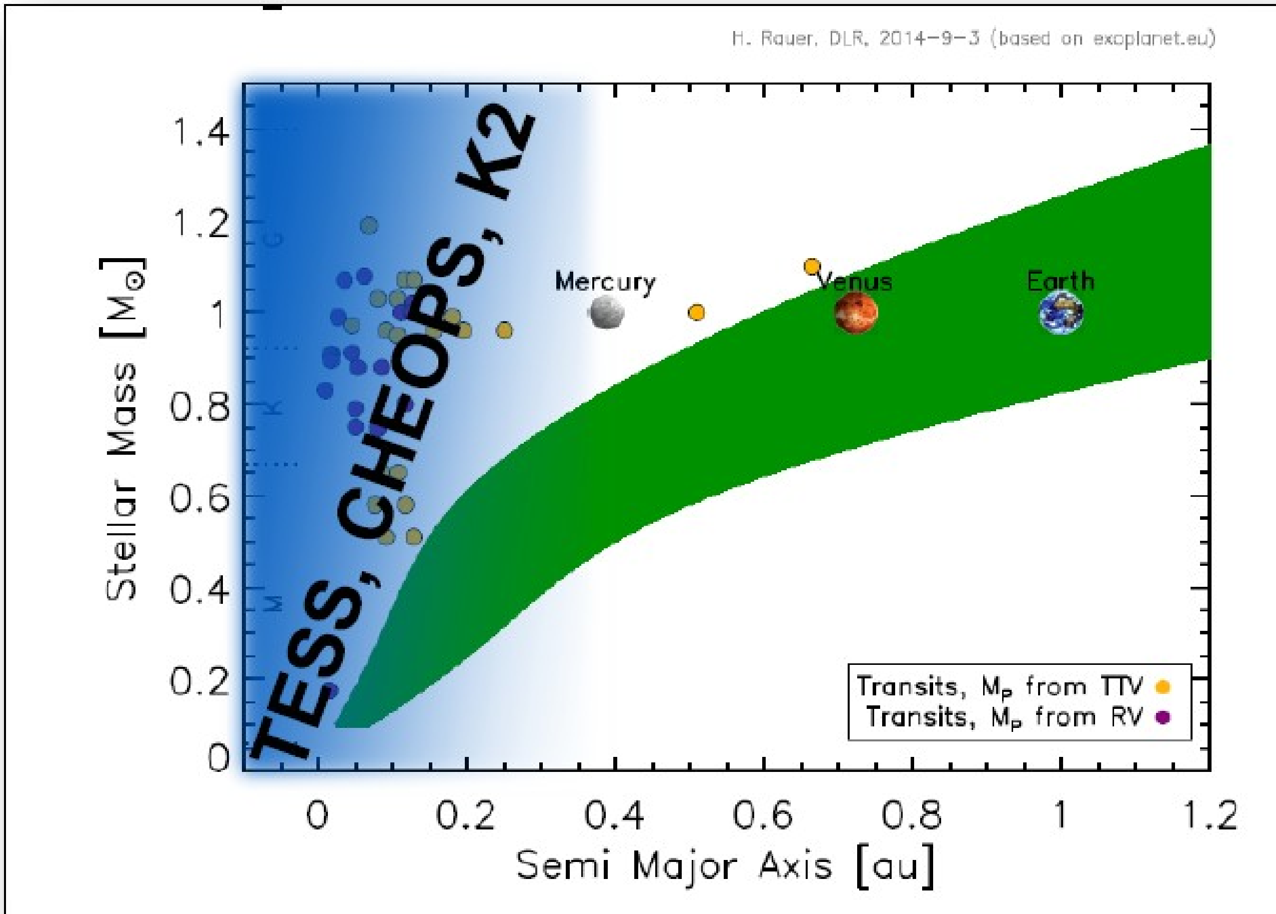
7. Future

… or why we need better precision



H. Rauer, DLR, 2014-5-20 (based on exoplanet.eu)
Radius [Earth radii]
Mass [Earth masses]
0
2
4
6
8
0
5
10
15
20
25
30
Ice
Silicate
Iron
PLATO error bar

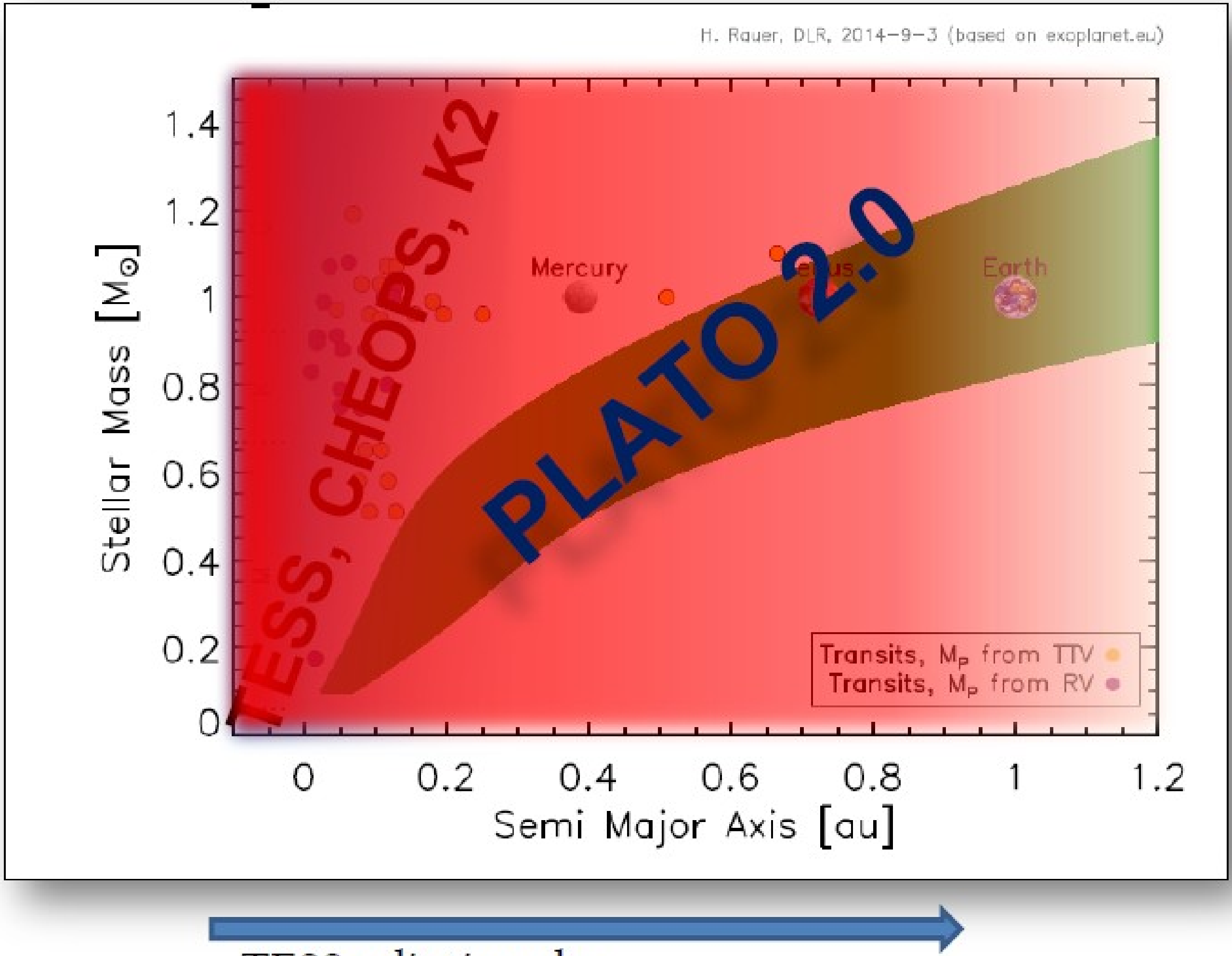
„Super-Earths“ with characterized radius and mass



- TESS, CHEOPS, K2 will mainly cover orbital periods up to ~80 days

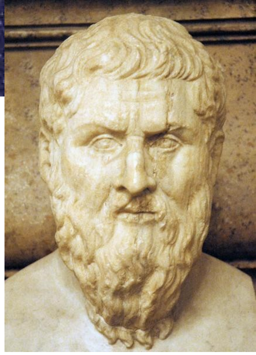
TESS ecliptic poles

„Super-Earths" with characterized radius and mass



TESS ecliptic poles

- PLATO 2.0 goal: Detect and characterize planets up to the habitable zone of solar-like stars.



PLAnetary Transits & Oscillations of stars

***PLATO** = next generation mission for ultra-high precision photometry*
for exoplanet search and stellar seismology

under assessment study at ESA in framework of Cosmic Vision programme

Πλατων

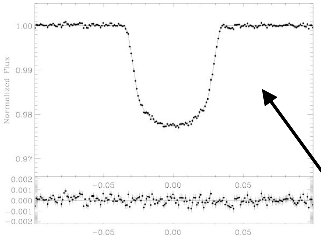
main objective : evolution of exoplanetary systems (= planets + host stars)

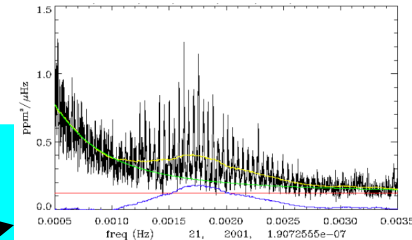
- a complete & precise characterisation of host stars is necessary to measure exoplanet properties: mass, radius, age

- compare planetary systems at various stages of evolution

- correlation of planet evolution with that of their host stars

= comparative exoplanetology





needed observations :

1. detection & characterisation of planetary transits

2. seismic analysis of exoplanet host stars

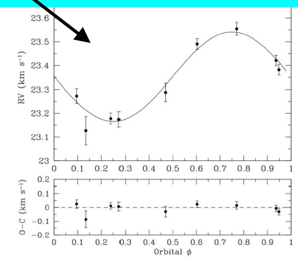
3. complementary ground based follow-up (spectroscopy)

- R_*, M_*, age

- interior

- exoplanet detection

- P_{orb}, R_p/R_*, R_*/a, $M^{1/3}/R_*$



- exoplanet confirmation

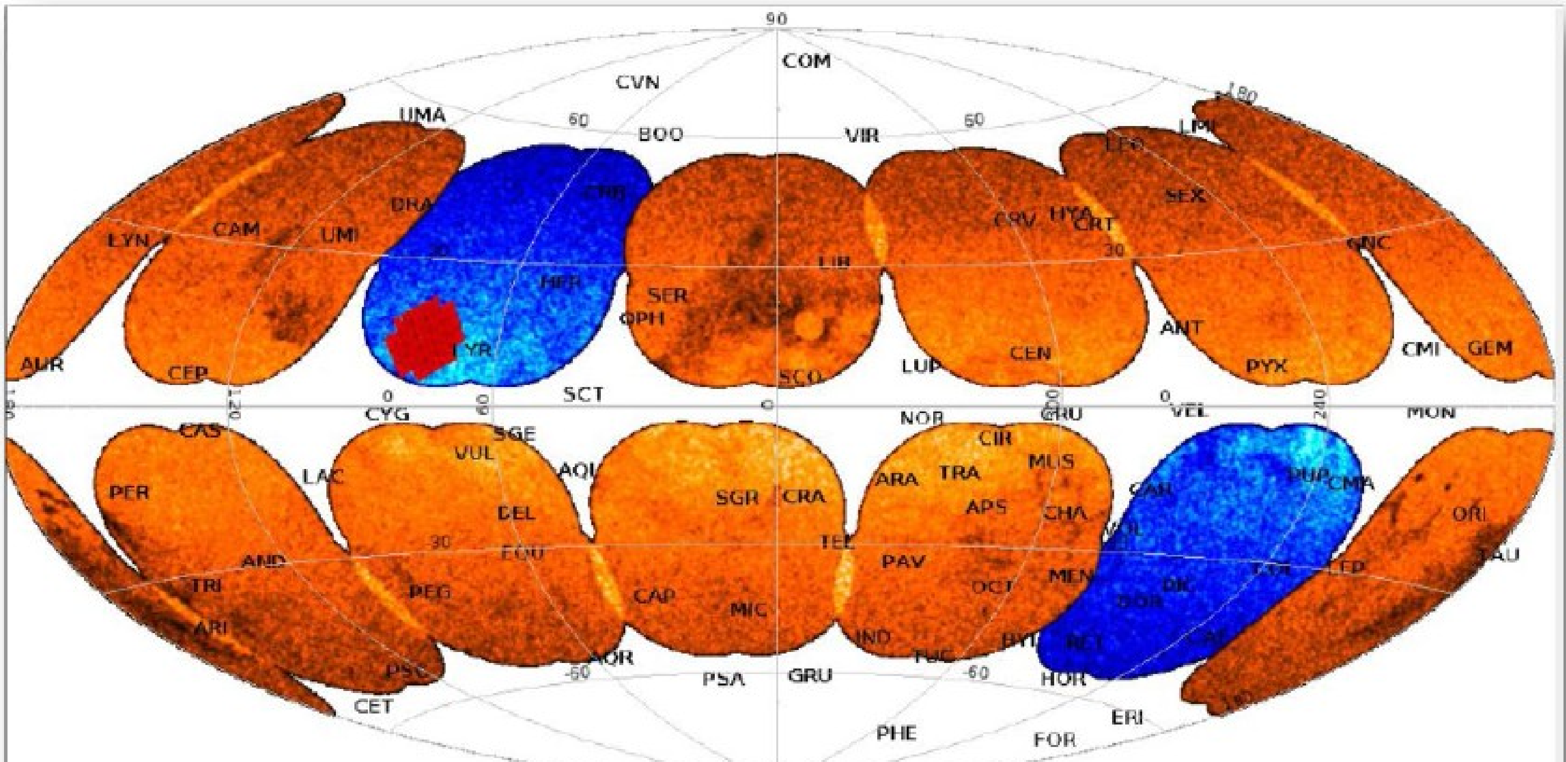
- $M_p/M_*^{2/3}$

- chemical composition of host stars

- … and of exoplanet atmospheres

PLATO 2.0 Sky

- A baseline observing strategy has been defined for mission design:
  - 6 years nominal science operation:
    - 2 long pointings of 2-3 years
    - step-and-stare phase (2-5 months per pointing)
- The final observing strategy will be fixed ~3 yrs (tbd) before launch.



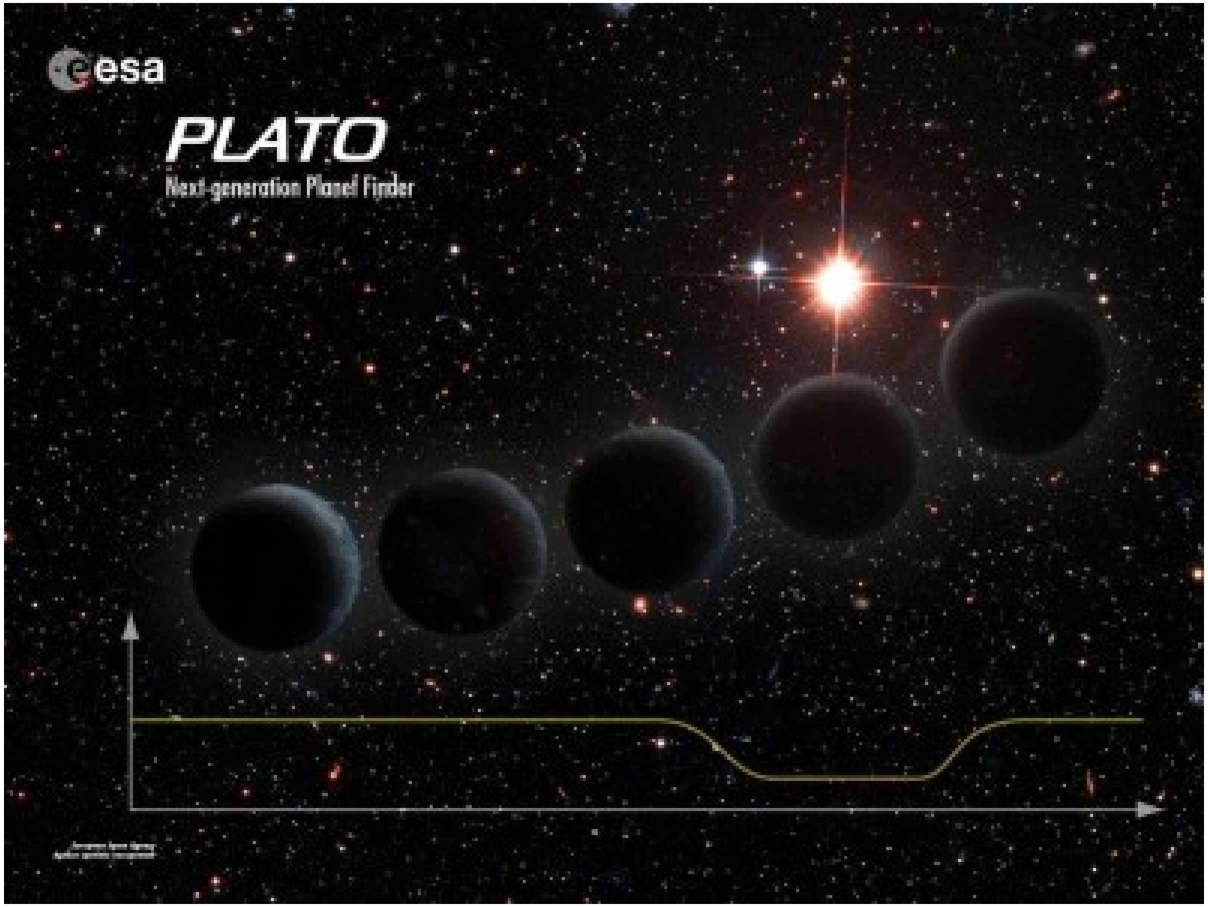
Future prospects

2006 — **CoRoT** (CNES)

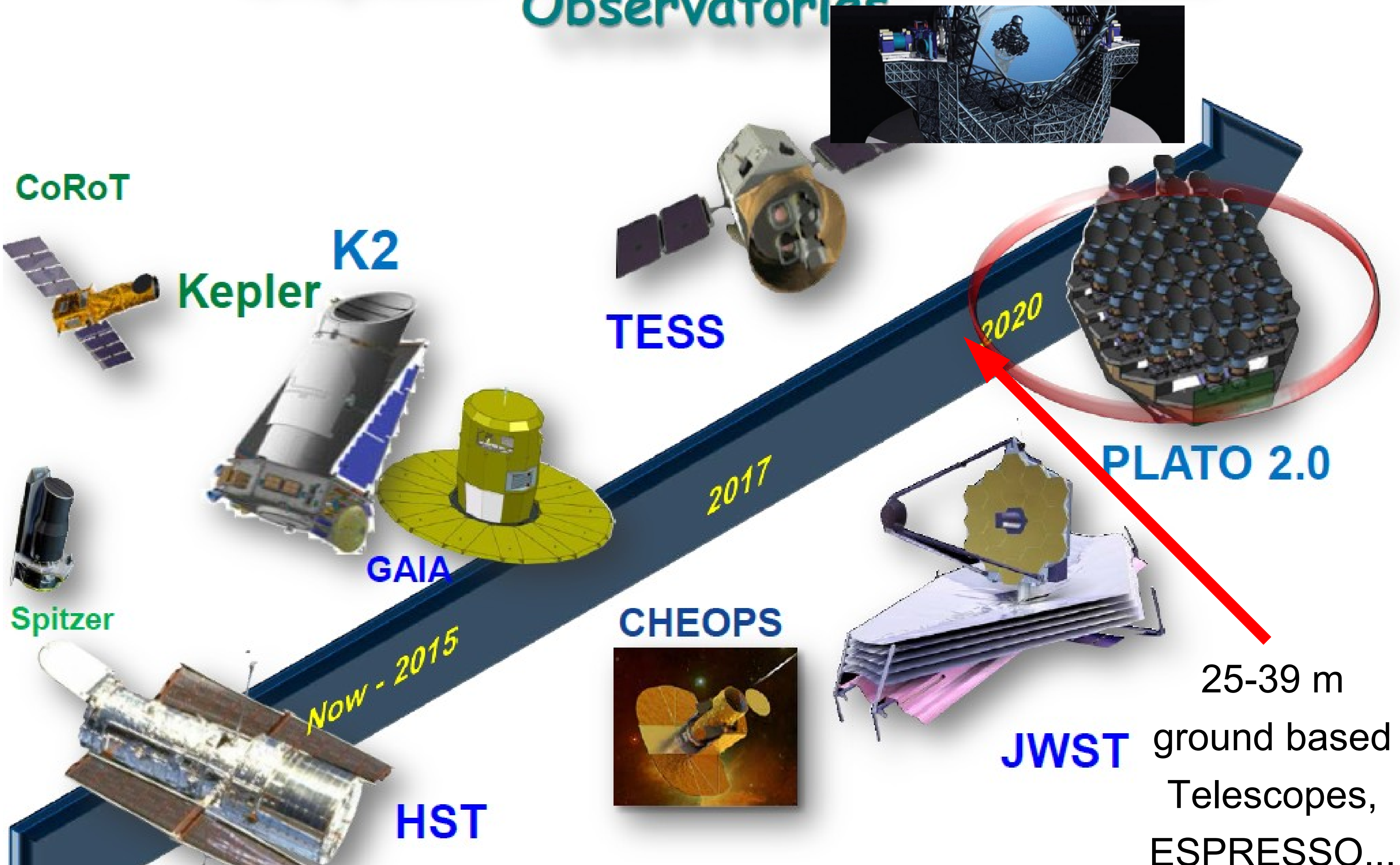
2008 — **Kepler** (NASA)

2014 — **Gaia** (ESA)

2024 (cosmic vision) — **PLATO?** (ESA)



Exoplanet Space Missions and Space Observatories



Thank you for your attention!